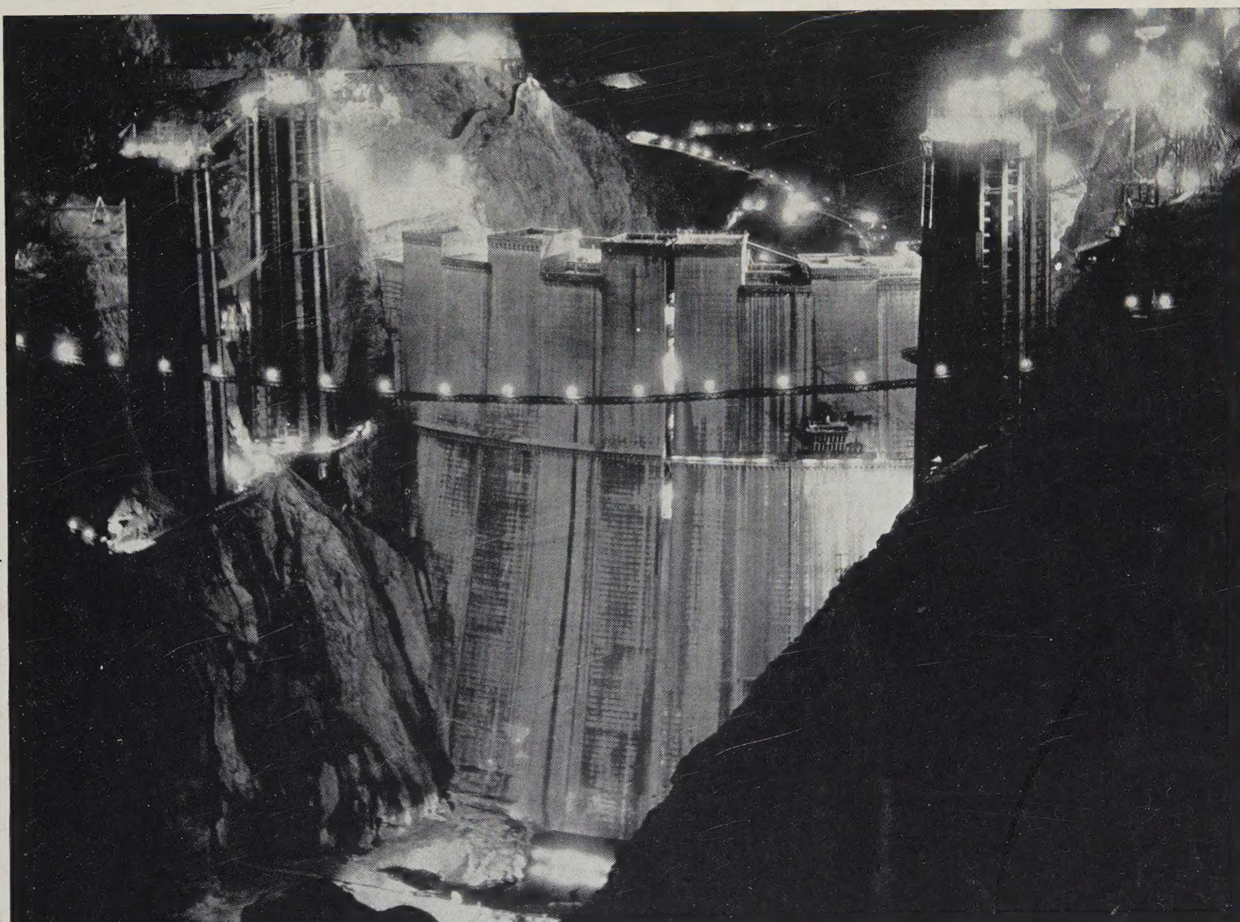
Electrical Engineering

March
1935



Published Monthly by the
American Institute of Electrical Engineers

Published Monthly by

American Institute of Electrical Engineers

(Founded May 13, 1884)

Electrical Engineering

Registered U. S. Patent Office

March 1935
Volume 54
No. 3

The Official Monthly Journal and Transactions of the A.I.E.E.

PUBLICATION OFFICE, 20th and Northampton Streets, Easton, Pa.

EDITORIAL AND ADVERTISING OFFICES, 33 West 39th Street, New York, N. Y.

ENTERED as second class matter at the Post Office, Easton, Pa., April 20, 1932, under the Act of Congress March 3, 1879. Accepted for mailing at special postage rates provided for in Section 1103, Act of October 3, 1917, authorized on August 3, 1918.

SUBSCRIPTION RATES—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, and the Philippine Islands, Central America, South America, Haiti, Spain, and Spanish Colonies, $13 to Canada, $14 to all other countries. Single copy $1.50.

CHANGE OF ADDRESS—requests must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered due to incorrect address cannot be replaced without charge. Be sure to specify both old and new addresses and any change in business affiliation.

ADVERTISING COPY—changes must be received by the fifteenth of the month to be effective for the issue of the month succeeding.

ELECTRICAL ENGINEERING is indexed in Industrial Arts Index and Engineering Index.

Printed in the United States of America. Number of copies this issue—18,500

Front Cover

Boulder Dam, on the Colorado River between Arizona and Nevada, some 30 miles southeast of Las Vegas, Nev. This night view of the upstream face of the dam and appurtenant works was taken on October 20, 1934.

Photo courtesy U. S. Bureau of Reclamation, Department of the Interior

Special Articles

A.I.E.E. Papers

Discussions

Cables

Power Transmission

News of Institute and Related Activities 336

A Power Company Communication System

By interconnecting and coördinating its private communication facilities with the commercial telephone system, the Tennessee Electric Power Company is building up a comprehensive communication system for the use of all departments of the company. These improved communication facilities are described briefly in this paper. The principal features of the plan are: (1) adequate interconnecting facilities between telephone and power company systems are furnished by the telephone company; (2) telephone equipment retired by the power company is replaced by telephone company equipment; and (3) commercial leased service is considered whenever the power company requires additional facilities.

By
E. E. GEORGE
MEMBER A.I.E.E.
The Tennessee Elec. Pwr. Co., Chattanooga, Tenn.

O. J. HUIE
MEMBER A.I.E.E.
Southern Bell Tel. and Tel. Co. Atlanta, Ga.

ARRANGEMENTS for load dispatching and other communication services recently devised and installed for the Tennessee Electric Power Company are described in this paper. It is offered as a contribution to the subject of equipment arrangements mentioned in an earlier paper. ("Communication Services of Electric Utilities, Underlying Considerations," R. N. Conwell, G. M. Keenan, C. F. Craig, and E. C. Briggs, A.I.E.E. Transactions, volume 50, 1931, pages 1285–91.)

Before plans for these arrangements were initiated, the power company was served by 2 practically independent communication systems: (1) the local administrative and commercial departments using commercial private-branch-exchange and exchange facilities, and (2) the operating department using a long private line system built and maintained entirely by the power company. There was only one point of interconnection between the 2 systems and it was incidental and inadequate. The power company had built much of its private telephone system years ago when patrol lines along the transmission line right of way were considered essential. Since that time improved reliability of transmission lines, increased accessibility to right of way, and increased availability of commercial telephone circuits in rural localities and villages, have all served to reduce the need for confining telephone lines to transmission line right of way. Other factors have reduced the necessity for power company owned telephone facilities, such as broader interconnecting privileges with commercial telephone systems, rerouting service on leased lines, and improvements in speed and reliability of commercial telephone service. Sensing these changed conditions, and realizing the manifold advantages of a comprehensive telephone system serving all departments and localities without duplication of instrumentalities, the power company in 1930 signed a general contract with the Southern Bell Telephone and Telegraph Company, looking to a program for improving its communication services by interconnecting and coördinating its private facilities with the commercial telephone system.

Following the contract, the engineers of the telephone and power companies made a joint study of the communication system and requirements of the power company, and planned in detail the steps necessary to carry out the intentions of the contract.

The Tennessee Electric Power Company serves an area in central and east Tennessee about 100 miles wide and 300 miles long, including the important cities of Nashville and Chattanooga. Power is generated at 8 plants, and is interchanged with contiguous systems. In its communication system are more than 1,000 miles of telephone circuit, partly leased, but principally owned by the power company. The headquarters office is in Chattanooga. It has a private branch exchange and associated with it a customers' service switchboard; in addition, the territorial telephone lines of the power company are centered there. The chief dispatcher is located there and subdispatchers are stationed at Nashville and Knoxville. Figure 1 shows these points and other system stations. An inspection of this diagram indicates the general situation dealt with and the switching points requiring special design considerations to render the necessary service. Design also necessitated consideration of the fact that the 3 cities named have dial services, and at Chattanooga the power company's private branch exchange is of the dial type.

The general plan covered the following main features and requirements:

1. Adequate interconnecting facilities between the commercial telephone system and the power company system to be furnished by the telephone company and to be designed particularly for this service.

2. Power company telephone equipment to be replaced by telephone company equipment as it wore out, became inadequate, or otherwise justified retirement in favor of leased service.

3. Commercial leased service to be considered whenever additions to the power company's communication system were required.

As a part of the first requirement, a dispatch switchboard has been designed and installed at Chattanooga, and subdispatch turrets have been

A paper recommended for publication by the A.I.E.E. committee on communication, and scheduled for discussion at the South West District meeting, Oklahoma City, Okla., April 24–26, 1935. Manuscript submitted June 14, 1934; released for publication Feb. 4, 1935.

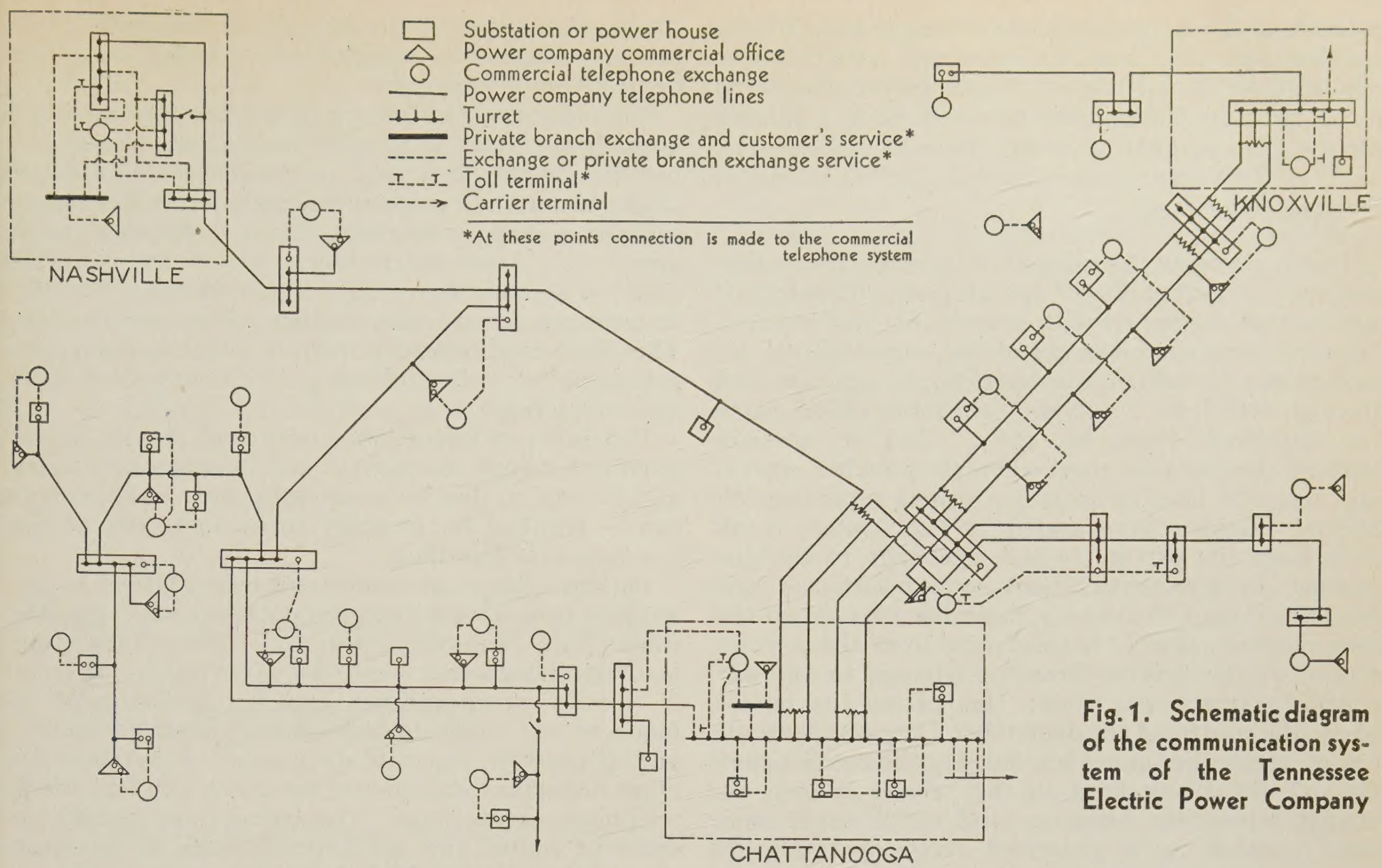


Fig. 1. Schematic diagram of the communication system of the Tennessee Electric Power Company

located at Nashville (West Nashville substation) and Knoxville (Arlington substation).

Dispatchers' and Subdispatchers' Turrets

It was necessary for the turrets (the dispatch switchboard is composed of several detached positions called "turrets") to accommodate and permit switching between a great variety of lines, including: long magneto lines both exposed and unexposed; short magneto lines to local substations; trunk lines to and from the dial private branch exchange; trunk lines to and from dial central office; 2-way common battery toll terminal trunk lines connecting with the toll board; common battery lines in headquarters building; tie trunk lines between turrets. With this variety of lines, it is readily seen that to design a turret to give uniform operation and inter-connection to all lines is an interesting and important problem. Furthermore, the method of operation of the Chattanooga installation is different from the usual power company telephone system in that all calls over the power company long lines, whether operating, commercial, or administrative, are handled and switched by the system load dispatcher, whereas in many systems the load dispatchers handle operating calls only, and the private branch exchange operators handle the commercial and administrative calls.

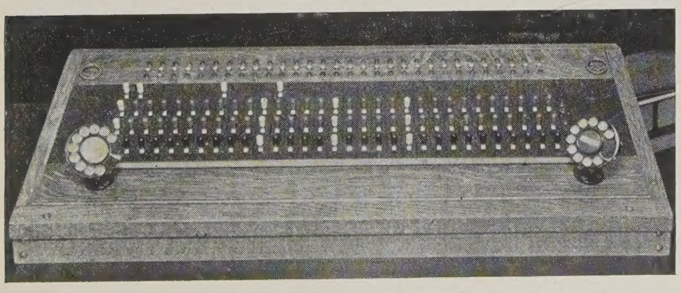


Fig. 2. Dispatcher's turret

The measure of traffic showed that 2 positions for normal service, and 2 supplementary key boxes for overloads at times of emergency, were necessary. Two one-position single-panel key-operated sloping-face turrets (figure 2) accordingly were designed and installed, together with 2 key boxes in which were multipled the more important lines, arranged for answering and calling but not for interconnection. The relays, coils, and other apparatus in the turret circuits are mounted on a 2-bay relay rack in an adjoining room, so that there is nothing in the turrets except keys and signal lamps. A dial is connected into each operator's telephone circuit and mounted conveniently on one end of the turret, while on the opposite end is a dial for controlling the automatic electric power diagram board.

The turrets are mounted on tables in such a way as to afford ample and convenient room for log sheets, orders, and other supervisory records. The 2 key boxes are mounted on desks, one at each end of the dispatch room, with the dispatch tables between and in line, and all facing the diagram board (figure 3). The whole is an attractive and convenient layout affording excellent working conditions and calculated to handle efficiently all dispatching operations under normal and abnormal plant conditions.

The subdispatchers' turrets each consist of one

position of a key operated switchboard resembling a cordless private branch exchange switchboard, equipped for 7 or 16 lines. These turrets are wired for 2 operators' telephone sets and have 4 talking busses, thus permitting 4 simultaneous connections.

Special Features

In order to gain the maximum in simplicity, speed, accuracy and reliability of operation, the dispatchers' turrets were equipped with several unusual features. No effort was spared in improving supervision (i. e., the means by which the operator is signaled and through which he is advised when the called party has answered, hung up, etc.). Dial or common battery circuits were used wherever possible, reserving magneto lines for intercity or long rural circuits. Special features were added to the inward trunk lines from the private branch exchange to the dispatcher to give switch-hook supervision, as this has been found to be very desirable on calls to the long magneto lines. A third wire from the selector switch at the private branch exchange to the dispatcher's turret was used; this places the circuit under the control of the dispatcher's key and prevents cut-off of the dial line when flashing the recall signal. On out-dial trunk lines to the private branch exchange answering, hang-up, and recall supervision were secured by a polarized relay operating on battery reversal from the connector.

Colored supervisory lamps were provided to permit distinctions between "waiting for the called party to answer" and "hang-up by the called party" on the common battery lines and private branch exchange trunk lines; this has been found to be particularly valuable to the load dispatcher.

The Chattanooga turrets tie magneto circuits directly together metallically, thus avoiding transmission loss where efficiency is needed most. Repeating coils are used on all common battery or dial circuits to provide for interconnection between the various types of circuits. It is also possible to put several lines of various kinds on the same bus for conference purposes.

All connections are put up by keys instead of cords, as such operation is simpler and faster. Each line has a separate listening and ringing key for the same reason. All incoming signals as well as rering signals give a permanent lamp indication until answered. A line alarm buzzer also is left continuously in service, but a key is provided so that the buzzer can be cut out during equipment trouble. The disconnect alarm buzzer is used similarly, resulting in very fast clearing of circuits after calls are completed.

Flexibility of operation is improved greatly by tie circuits between the turrets and between key boxes and turrets, so that lines appearing only in one turret can be trunked to the other turret or to one of the key boxes for handling.

Perhaps the most important contribution to reliability in local service is the provision of 2 separate routes into important stations. Every substation in Chattanooga and Nashville is served by at least 2 circuits over separate routes. An attempt is made to use separate pole routes, separate cables, and, if possible, separate duct runs. Practically all other important stations are served by 2 independent telephone connections. The circuits are usually on different routes and are kept separate as much as possible into the station building.

Every important station on the power company's private communication system now can be reached over commercial toll and exchange lines, the commercial system forming a secondary or back-up system over which, when necessary, business can be transacted as readily as over the private system. Figure 1 shows the points of interconnection and the schematic plan of the dual connecting arrangements, but does not, of course, show the commercial toll lines used.

The separation of inward and outward traffic routes is one of the important features of the tele-

Fig. 3. Dispatcher's room showing turrets on 2 desks in center and one of the key boxes on desk in right foreground

phone service in this system. This applies to general office private branch exchanges as well as to system dispatchers' turrets. Any extensive power failure in a local area results in a multitude of inward calls. To prevent such a volume of inward calls from cutting off the power company's outward service, one-way circuits in both directions for central office and private branch exchange connections are provided.

To facilitate the handling of calls to the load dispatcher from department heads and maintenance employees during times when all the city trunk lines of the power company private branch exchange are busy, 2 unlisted inward lines have been provided between the main exchange and the dispatchers' turrets. The numbers of these lines are known only to those employees who would have occasion to reach the dispatcher in such emergencies.

Progress on the Application of the Plan

In addition to the dispatchers' turrets and their various connections, the unification and coördination plan has been carried out at all substations in the larger cities. Whenever changes were required at any given station, advantage was taken of the opportunity to make that station conform to the plan of coördinated facilities.

An Advanced Course in Engineering

To supplement the training of college graduates in the practical application of fundamental principles and mathematics to engineering analysis, the General Electric Company 11 years ago established its "Advanced Course in Engineering." The course of study given and the objectives to be attained are outlined in this paper which also summarizes the practical value of this special 3 year course as indicated by the work of its graduates.

By
A. R. STEVENSON, JR.
ASSOCIATE A.I.E.E.

ALAN HOWARD
ASSOCIATE A.I.E.E.

Both of
General Electric Co.,
Schenectady, N. Y.

IN the pioneer era of the General Electric Company, men like Steinmetz, Berg, and Faccioli, all of whom had received their education abroad, furnished the mathematical foundation for the design of apparatus. There then followed a period when engineers were kept extremely busy designing machines, using the heritage of formulas which had been passed on to them by these older men. Relatively little time was taken for extending and improving the theoretical foundation. There was, in other words, an era of what might be called "handbook engineering." This condition, if permitted to exist too long, was bound to lead to a slowing down of progress. The company realized that its achievement thus far had rested in a large measure upon the sound technical foundation laid by the pioneers, and that future progress would depend on filling their places with high caliber men of broad technical training who had the ability to think along fundamental lines and to apply their knowledge to the development of improved apparatus. The full realization of this just after the World War, when things were being arranged on a peace time basis, led the company to establish the advanced course in engineering to train men who could deal with the advanced theoretical aspects of engineering work.

Such work is essentially mathematical in character. This is especially true in electrical engineering, in which one deals with quantities that are more intangible than those in other branches of engineering. Thus in order to deal effectively with such problems one must be able to use mathematics as a tool in the application of the fundamental laws of physics to the problems of engineering, and must have a real appreciation of its significance as an aid in straight thinking.

Engineering graduates from American colleges, however, usually did not have sufficient training along these lines. Most of them had no mathematical training beyond the calculus, and those who had studied differential equations had not learned how to make use of them in the analysis of physical problems. There were coming to the company many excellent, ingenious designers, but relatively few who were thoroughly grounded in methods of analysis. The courses in many colleges had become too practical; men were being taught routine rule of thumb methods of design, and there was insufficient emphasis on thinking problems through by the use of fundamental principles.

At that time the company was recruiting from the technical schools about 400 or 500 men each year. These men entered the testing department, where

A paper recommended for publication by the A.I.E.E. committee on education, and scheduled for discussion at the A.I.E.E. summer convention, Ithaca, N. Y., June 24–28, 1935. Manuscript submitted December 28, 1934; released for publication Feb. 1, 1935.

they usually stayed at least a year. About half of this number, after a year or 2 of training, would leave the company to take outside positions; the rest would be distributed throughout the extended activities of the company in commercial, sales, and design engineering. There was, however, no definite, effective training program for those interested in the more technical phases of engineering.

Advanced Course Instituted

After thorough study and planning the "advanced course in engineering" was started in the fall of 1923 under the direction of R. E. Doherty and A. R. Stevenson, Jr., both of whom had been pupils of Doctors Steinmetz and Berg and therefore were prepared in some measure to help guide a new generation to carry on and expand the traditions which had been passed on to them.

The course was instituted primarily to train design engineers so that for the most part only men interested in design work were chosen for it. It was realized from the first that it was impossible to create ability and that it was necessary to select men with creative ability and a high natural aptitude for design, then arrange the course to give them an opportunity to improve themselves, gain experience, and ultimately find positions where they could apply their talents to the best advantage.

The experience of the founders of the course and of those with whom they were associated indicated very definitely that in order to be effective the course should have 2 major objects. These objects were to train men

1. To apply the fundamental principles of engineering to the solution of their problems.

2. To present the results of their work clearly and concisely, whether in written form or orally, so that others might easily understand and use these results.

In the 11 years since its founding these objectives of the course have been adhered to.

During the first few years of its existence, the course was mainly electrical, but as the years went by it was realized that there was great need for similar training in mechanical engineering. Much of the work in electrical design departments required mechanical, as well as electrical engineering, and there were many mechanical engineering departments, such as turbine, refrigerator, and air conditioning. Therefore, the course was expanded somewhat to include the fundamentals of elasticity, dynamics, and heat transfer, and to extend the study of thermodynamics.

Present Organization

The course is organized at present on essentially the same basis as it was during the first years of its existence, although many changes have been made based on experience. It may, therefore, be of interest briefly to describe this present organization.

The complete course comprises 3 years, with about 30 men in the first year, or *A* class, of whom from 8 to 10 are selected to continue for 2 more years in the *B* and *C* classes.

The *A* class is formed from members of the testing department who have been with the company only a short time. Entrance is competitive and selection is made from among the applicants on the basis of an examination, school records, and personal interviews. Personality and ability to coöperate with others are carefully considered, as well as technical ability.

Those selected remain in the testing department and obtain the same experience there as those not taking the course. In addition, they spend a half day a week in class on company time.

The work during the first year consists of a study of the application of the fundamentals of engineering to the solution of problems involving mechanics, thermodynamics, heat transfer, electricity, and magnetism. The specific objects are:

1. To show that the same fundamental laws, such as the law of the conservation of energy, apply in all of these fields.

2. To train the men to think out problems for themselves by using these fundamental laws.

3. To teach them to select the pertinent data necessary to a particular problem from a miscellaneous mass of known facts.

4. To extend their grasp of mathematics as required in the study of problems in these various fields of engineering.

5. To show them how to use common sense engineering ideas in the simplification of mathematics.

6. To engender the conviction that there is an answer to every problem, which can and must be reached even if laborious step by step methods are required.

7. To teach them to criticize their own answers, and to determine with certainty by judgment and common sense comparison with other known solutions whether the answer is right.

8. To train them to present ideas clearly, concisely, and attractively.

These objects are carried out by a program of classroom lectures and by assigning engineering problems each week which the students solve at home and turn in at the following class. As far as possible the problems selected are ones which have actually arisen in the engineering departments of the company. In many cases unsolved problems have been assigned, and the classes have thus been given the chance to be of assistance in useful engineering work. These problems differ from most textbook problems in that the students are expected to select from a group of facts those which are necessary for the solution. Another important aspect is that usually it is necessary for the students to make a number of simplifying assumptions in order to bring the problem within the range of practical mathematics.

The assignments usually consist of only one major problem rather than a group of miscellaneous shorter ones. This method is used because the problems which can be assigned approach more closely the type which the men will encounter in their future engineering work.

The solutions of these problems are written up as engineering reports so that the students will become proficient in presenting the results of their work in this form. These reports are constructively criticized on the basis of both the technical work and the quality of presentation, and are given numerical grades.

In addition to the technical lectures, informative talks are given on various phases of engineering and company activities by members of many departments, and instruction in public speaking is given by a member of the faculty of Union College.

Since the organization of the course, the students have entered into this program with great enthusiasm, putting an average of about 15 to 20 hours outside time each week on their home work. The class really sets its own pace. A few men fall by the wayside, but nearly all those entering the *A* class complete it.

Conduct of *B* and *C* Classes

By the end of the first year, the men have received a thorough grounding in the basic methods of solving engineering problems and have sufficient mathematics for most engineering purposes. They are well qualified to enter design engineering departments, and most of those not selected for the *B* class do this soon after graduating. Those continuing with the *B* class leave the testing department and are taken directly on to the payroll of the advanced course. While on this payroll, the men are placed in engineering departments on assignments lasting 3 to 4 months each, in which they do real engineering work and obtain a good insight of the work of the department. As many as possible of the men are assigned for several months to a district office engineering department, with the idea of giving them the customer's viewpoint.

A knowledge of factory processes, and a real appreciation of the factors affecting cost, are of prime importance to designers, and this phase of engineering is receiving more and more emphasis in the course. As many as possible of the second and third year men are assigned to the factory for periods of about 6 months in order to obtain this type of training.

Meanwhile the classroom work of a half day a week is continued. Some of the *B* class men enter the electrical engineering section while others enter the thermal engineering section. In the first a further study is made of the fundamentals of flux distribution, after which transformers, induction motors, and synchronous and d-c machines are taken up, followed by a fundamental study of electron tubes, rectifiers, and inverters. Those entering the second make a further study of thermodynamics, heat transfer, and fluid flow, with the application of these to the design of refrigerators, air conditioning apparatus, and turbines.

In the last year, or *C* class, the men recombine in the mechanical engineering section. In this section elasticity, dynamics, hydrodynamics, and heat transmission are studied and applied to the analysis of stresses and vibrations in machines, cooling problems, and lubrication. During part of the year the class divides and those who previously took the electrical engineering section study heat transfer with the thermal engineering section, while those who previously took the thermal engineering section study the more elementary theory of electrical machinery.

During these last 2 years the men continue to put in considerable time on their home work which still consists mainly of the solution of problems. The problems assigned of course become more difficult and complex, and less and less detailed guidance is given the students in making the necessary assumptions and deciding on methods of attack.

Each section of the course has an individual supervisor who is either a graduate or a member of the course. He devotes the majority of his time directly to the work, but also spends considerable time on engineering. This latter activity is considered quite important since it serves to help keep the course in direct contact with the regular engineering work of the company, and gives the supervisor a broader experience. No individual supervises a section for more than one year.

The technical lectures in all sections are given by a great many men from many different departments. In this way, the subjects are presented from many different points of view and there is little danger of the course becoming "inbred."

Under this program, by the end of the 3 years the men have received a very thorough training in all of the more important theoretical aspects of machine analysis and design, and have had considerable varied engineering experience. They are well equipped to solve problems in stresses, machine vibration, lubrication, and cooling as well as those of a purely electrical nature. The men who will go into electrical engineering departments spend about $^2/_3$ of the time in the course studying mechanical engineering subjects. Those expecting to take up more purely mechanical engineering work receive a very similar training with a little less emphasis on the electrical work.

Results Achieved by the Course

The course has been operating about 11 years, and a total of 309 men have been graduated from it (at present there are 31 men in *A* class, 10 in the *B* class, and 8 in the *C* class). Of this number 185 or 60 per cent are still with the company.

Seventy men have been graduated from the complete 3 years of the course and of these 56 or 80 per cent are still with the company. This high percentage remaining after several years of depression is a significant indication of the excellent work these men are doing. It is particularly significant because of the 14 men who have left, all but one left entirely voluntarily to accept other positions.

Graduates of the course have contributed considerably to the technical literature. Some of the more notable of these contributions have been L. V. Bewley's many papers on traveling waves and lightning phenomena, culminating in his multivelocity theory. R. H. Park greatly advanced the theoretical analysis of synchronous machines and power system stability in his papers on these subjects. W. J. King has published many basic papers on heat transmission, including a comprehensive series of 6 articles in *Mechanical Engineering*. A paper by F. M. Starr on equivalent circuits

won the Alfred Noble prize award in 1932. As a whole, the advanced course graduates have contributed more than 85 national society papers and *General Electric Review* articles, and in addition they have presented numerous discussions and have written a large number of articles for the trade journals.

Within the company the graduates have contributed much to its engineering and have assumed relatively great responsibilities, considering their comparatively short experience. Several have been given responsible charge of the design work in their departments, and several have had their work recognized by a Coffin Award (a company award "for the most signal contributions towards increase of efficiency or progress in the electrical art").

The course has, it is believed, definitely proved its fundamental value through the outstanding accomplishments of its graduates, and it consequently has been actively maintained throughout the past few years of depression.

Similarity Relations in Electrical Engineering

The application of dimensional analysis to various types of problems in electrical engineering is discussed in this paper for the purpose of stimulating the use of model experiments in solving these problems. The authors hold that this method can be applied to many electrical engineering problems that are difficult of solution otherwise. Criterions for determining whether or not dimensional analysis and model experiments can be used are given.

By
J. G. BRAINERD
ASSOCIATE A.I.E.E.

JACOB NEUFELD
ENROLLED STUDENT

Both of the Moore School of Electrical Engineering, University of Pennsylvania, Philadelphia

THE widespread use of model experiments by mechanical and civil engineers has found a much smaller counterpart in electrical engineering. This may be because opportunity is not at hand, but the relative lack of discussion of such tests in electrical engineering journals and the almost complete absence of any reference to them in college textbooks for electrical engineering students make it appear possible that dimensional analysis—the theory on which model experiments are based—is not widely recognized as a tool for investigation in the field.[1] By model experiment is meant one such that the results of tests on one object (the model) can be applied to an entire class of similar objects according to definite rules (similarity relations) deduced by use of dimensional analysis. The term dimensional analysis is a broad one covering changing of units, checking of equations dimensionally, and development of similarity relations, of which only the last is considered in this paper. Certain devices, for example power system calculating boards, are not models in the sense the word is used here.

As an illustration of a model experiment consider the work of Forbes and Gorman[2] who measured the resistance of certain conductors at high frequencies, and by a similarity relationship applied the result of their measurements to bus bars at low frequencies. The advantage of a model experiment in this case was that the frequency at which the measurements were made was chosen to suit experimental conditions. To have determined skin effect directly in the bus bars at the frequency at which the result was desired would have been a far more difficult task. Dwight[3] has referred to similar experiments.

In place of a second example, there may be listed a number of important problems in which model experiments, if possible, might prove helpful: lightning investigations, some radio transmission problems, electric furnace design,[4] determination of current distribution in the earth due to ground return circuits, cable problems, etc. Indeed there seem to have been few technical problems investigated from this point of view and the list of the potentialities could be expanded greatly. (In many cases, however, model experiments would not be worth using even if they could be utilized.)

To take a particular case, in recent years extensive lightning investigations have been conducted. These have been expensive and laborious. Would it not have been possible to obtain by model experiments much of the information needed? An answer to this cannot be given here—a thorough acquaintance with the field of application is usually necessary for the use of dimensional analysis. But the problem does not seem on the surface to be more difficult than the aerodynamical one in which models are tested in wind tunnels, and until a negative answer can be proved, there is no reason to believe that model experiments in the lighting case are not possible and, incidently, probably far cheaper.

A Theorem of Dimensional Analysis

It is the purpose here to deduce some similarity relations using different methods to illustrate several ways of applying dimensional theory. As a preliminary it will be necessary to introduce some defini-

A paper recommended for publication by the A.I.E.E. committee on electrophysics, and tentatively scheduled for discussion at the A.I.E.E. summer convention, Ithaca, N. Y., June 24–28, 1935. Manuscript submitted April 10, 1934; released for publication Sept. 27, 1934.

1. For all numbered references, see list at end of paper.

tions and a theorem which need not be proved in this paper.[5]

a. *A fundamental quantity* is any quantity such as mass M, length L, time T, etc., in terms of which the dimensions of a given quantity can be expressed. Thus the dimensions of resistance are LT^{-1} in electromagnetic units. All quantities of interest here have dimensional formulas which can be expressed as products of powers of fundamental quantities.

b. An equation is said to be *complete* when its form is not changed by any change in the size of fundamental units. Dimensional analysis can be used only in problems governed by an equation of this type.

c. If there are n quantities entering into a complete equation and m fundamental units, there are $n-m$ independent dimensionless products of some or all of the quantities, and there exists an equation of the form

$$F(\pi_1, \pi_2, \ldots\ldots, \pi_{n-m}) = 0 \tag{1}$$

where π's are the $n-m$ dimensionless products. (This is the so-called π Theorem.)

An Application of the Theorem

As an illustration of one method of dimensional analysis the formula used by Forbes and Gorman may be deduced. It is desired to determine the total resistance per unit length (r_{a-c}) of a bus bar of given shape and area A of cross section, carrying a current of frequency f. Assume that r_{a-c} depends upon A, f, and the specific resistivity of the material ρ. Then by (a) and (c) above, since the dimensional formula of resistance is LT^{-1} (in electromagnetic units) and that of resistance per unit length is T^{-1}

$$T^{-1} = (L^{2p})(T^{-q})(L^{2s}T^{-s}) = A^p f^q \rho^s \tag{2}$$

the left-hand side of the first equality being the dimensions of r_{a-c} and the right hand side those of A, f and ρ raised to powers p, q, s, respectively. Here there are 4 quantities, r_{a-c}, A, f, and ρ, entering and 2 fundamental quantities L and T. Hence $n=4$, $m=2$, and by (c) there are 2 dimensionless products, one of which is $TL^{2p}T^{-q}L^{2s}T^{-s}$ obtained by multiplying both sides of equation 2 by T. For equation 2 to be consistent, the powers of each fundamental quantity must be equal on the 2 sides of the equation. Hence

$$0 = 2p + 2s; \qquad -1 = -q-s$$
$$s = 1-q; \qquad p = -1 + q$$

whence

$$T^{-1} = A^p f^q \rho^s = A^{-+1q} f^q \rho^{1-q} = \rho A^{-1}[A^q f^q \rho^{-q}]$$
$$= \rho A^{-1}\left[\frac{Af}{\rho}\right]^q \tag{3}$$

Therefore r_{a-c} is a sum of terms of the form $\rho A^{-1} \times (Af/\rho)^q$. Since no other condition exists from which q can be determined, q is entirely arbitrary and r_{a-c} may be written

$$r_{a-c} = \frac{\rho}{A}\,\varphi\left(\frac{Af}{\rho}\right)$$

where φ denotes an arbitrary function. But ρA^{-1} is the d-c resistance per unit length r_{d-c}, hence finally

$$\frac{r_{a-c}}{r_{d-c}} = \varphi\left(\frac{Af}{\rho}\right) \tag{4}$$

This equation states that so long as the product Af/ρ remains constant, the quantities A, f, and ρ can take on any values, without altering the left-hand side. Thus in the case of the bus bar, a rod of similar cross sectional shape but different area A' and of different resistivity ρ' has the same ratio of a-c to d-c resistance at a frequency f' as the bus bar with A, ρ, f parameters provided

$$\frac{A'f'}{\rho'} = \frac{Af}{\rho} \tag{5}$$

There are several points to be noticed in the above example:

1. It was only by a judicious choice of quantities involved that equation 2 could be written. This emphasizes the point that it requires a background of knowledge in a given field to use dimensional analysis for the derivation of similarity relations in that field.

2. Only one of the 2 possible dimensionless products was used, but equation 4 shows that the other one is r_{a-c}/r_{d-c}. An equation corresponding to equation 1 thus exists.

3. The advantages of dimensional analysis are illustrated: solving the differential equations applicable to the problem has been avoided (these equations are intractable in any save the simplest cases) and a very simple mathematical process substituted; model experiments are shown to be possible.

Equation 4 is a special case of a much more general relationship and it is the purpose of the next paragraphs to prove this. To illustrate another method of deducing similarity relations, the more general relationship will be derived in a different manner which is particularly applicable when differential equations are given.

Example of a Different Method of Deducing Similarity Relations

There are many problems which depend upon the distribution of currents, and electric and magnetic fields. Among these are problems of inductance, resistance, skin effect, proximity effect, radio transmission, eddy currents, etc. All of these problems are governed by the fundamental equations of electromagnetism (see appendix A) from which can be derived

$$\frac{4\pi}{c^2}(j\mu\gamma\omega - \mu k\omega^2)\mathrm{H}_x' = \nabla^2\mathrm{H}_x' \tag{6}$$

where $j \equiv \sqrt{-1}$, μ is the magnetic permeability, γ the specific conductivity k the dielectric permeability, c is a constant with dimensions of velocity ($c = 3 \times 10^{10}$ centimeters per second), ω is 2π times the frequency of the varying field, and H_x is the X component of the space vector $\boldsymbol{H}'$ representing this field which can be either a field of magnetic intensity, or of magnetic flux density $\boldsymbol{B}'$, or of electric field strength $\boldsymbol{E}'$ or of current density $\boldsymbol{J}'$. Similar equations exist for the Y and Z components. The term $\nabla^2 H_x'$ (see appendix B) may be considered for the present purpose simply as a second derivative of H_x' with respect to distance.

Equation 6 indicates that model experiments are possible. To prove this the following procedure may be used. Let A be any area "characteristic of" the original sample and of a group of models of this sample to which equation 6 applies. A varies among the members of the group. For convenience A may be taken perpendicular to the Z axis of a set of rec-

tangular axes XYZ and for simplicity the problem may be restricted to 2 dimensions. Write

$$x = c_x\sqrt{A}; \quad y = c_y\sqrt{A}$$

and write also

$$H' = c_H H_0; \quad \mu = c_\mu \mu_0; \quad \gamma = c_\gamma \gamma_0; \quad \omega = c_\omega \omega_0; \quad k = c_k k_0.$$

where H_0, μ_0, γ_0, ω_0, and k_0 are constants characteristic of any member of the group but may vary between members. Substituting in equation 6,

$$\frac{4\pi}{c^2}\left(jc_\mu c_\gamma c_\omega \mu_0 \gamma_0 \omega_0 - c_\mu c_k c_\omega^2 \mu_0 k_0 \omega_0^2\right) c_H H_{0x} = \frac{H_{0x}}{A}\left(\frac{\partial^2 c_H}{\partial c_x^2} + \frac{\partial^2 c_H}{\partial c_y^2}\right) \tag{7}$$

where H_{0_x} is the X component of H_0. A similar equation exists for H_{0_y}. Now if the original and its models are geometrically similar, A may vary from one to the other but c_x and c_y will be the same for all. It is assumed that μ_0, γ_0, ω_0, k_0, H_0 may differ among members of the group, but that c_μ, c_γ, c_ω, c_k, and c_H are the same at corresponding points; that is, the fields set up in the members of a group are geometrically similar (this is usually referred to as dynamical similarity). Then

$$\frac{\partial^2 c_H}{\partial c_x^2} + \frac{\partial^2 c_H}{\partial c_y^2} \tag{8}$$

must be the same for all geometrically similar models of a given original, and consequently

$$\frac{4\pi}{c^2} c_H A\left(jc_\mu c_\gamma c_\omega \mu_0 \gamma_0 \omega_0 - c_\mu c_K c^2{}_\omega \mu_0 k_0 \omega_0^2\right)$$

must be the same for this to be true. Hence if c_1 and c_2 are constants, the same for all models of a given sample,

$$\left.\begin{aligned} &\mu\gamma\omega A = c_1 \\ &\text{and} \\ &\mu k \omega^2 A = c_2 \end{aligned}\right\} \tag{9}$$

express the similarity conditions. That is, if equations 9 hold, a distribution of $\boldsymbol{H}$ (or $\boldsymbol{B}$, $\boldsymbol{J}$, or $\boldsymbol{E}$) will be obtained in the model which is exactly similar to that in the original, and quantities depending upon $\boldsymbol{H}$ (or $\boldsymbol{B}$, $\boldsymbol{J}$, or $\boldsymbol{E}$) will be related to corresponding quantities of the model in a definite manner. The 2 similarity conditions expressed by equations 9 cover the general case in which both conduction and displacement currents, or nonradiation and radiation fields, must be considered. If displacement currents and radiation may be neglected,

$$\mu\gamma\omega A = c_1$$

is sufficient. Comparing this with equation 5, it is seen that the 2 are intimately related; indeed the latter follows from the former at once except for the factor μ, accounted for below.

If conduction currents and nonradiation fields may be neglected, then

$$\mu k \omega^2 A = c_2$$

is sufficient for model experiments.

In the intermediate cases in which it is unknown *a priori* which class is concerned, the above conditions might be used in determining the classification. Grover and his students have done some work in this field,[6] not using the present method.

Boundary Conditions

There is one important limitation contained implicitly in the above argument—not only must the fundamental equations be satisfied, but certain boundary conditions also must be considered. This limitation should be borne in mind in determining similarity conditions in general.

Consider for example a cylindrical conductor with its axis parallel to a magnetic field, and let the problem be the investigation of the field in the conductor. The magnetic field may be produced in several ways; for example: (1) By a source outside of and at great distance from the conductor so that the magnetic field is uniform over the surface of the conductor; or (2) by a coil concentric with the conductor and of diameter slightly greater than that of the conductor. In case 2 there is obtained the "magnetic skin effect" and the distribution of the magnetic field is the same as the distribution of the current density in the case of electrical skin effect.

There are here 2 apparently similar problems. The same electromagnetic equations (appendix A) are involved and the physical boundary of the conductor is the same in whichever of the 2 fields the conductor is placed. The point of difference is that at the surface of the conductor different conditions hold:

Case 1: $\boldsymbol{H} = \text{constant}$
Case 2: $H_{T(\text{conductor})} = H_{T(\text{air})}$
and $\mu H_{N(\text{conductor})} = H_{N(\text{air})}$

where H_T is the tangential component and H_N the normal component of $\boldsymbol{H}$. The low frequency similarity relation $\mu\gamma\omega A = c_1$ holds only in case 1; in case 2 μ cannot be changed, i. e., the model must have the same μ as the original and the similarity relation is reduced to $\gamma\omega A = c_1'$.

Other Model Experiments

Potential model experiments in electrical engineering are by no means limited to those dependent solely upon the electromagnetic field equations. For example, model experiments might be used in studying the stability chracteristics of synchronous machines. The well known equation for the oscillation of the rotor of a synchronous motor to which a sudden load is applied is

$$P_i \frac{d^2\theta}{dt^2} + P_d \frac{d\theta}{dt} + P_m \sin\theta = P_L \tag{10}$$

where θ is the phase angle between the terminal potential and the electromotive force induced in the armature; $P_i = KI$ where I is the moment of inertia of the rotor and K a constant; $P_d = V^2/360fr_2$, approximately, where r_2 is the equivalent symmetrical rotor resistance per phase and V the magnitude of the voltage applied to the armature; $P_m = VE_1'/x_s$ where E_1' is the magnitude of the induced electromotive force in the armature due to the d-c field current and x_s is the synchronous reactance; and P_L is the shaft load suddenly applied to the motor.

It is evident that the values of the coefficients P_j, P_m, P_d, and P_L can be reduced considerably if the experiment is performed on a small model. At the same time the equation will remain invariant, hence the oscillations of the small model will give as much information as if the experiment were performed on the full size motor, in so far as equation 10 governs the motion. Moreover, if the measuring scale of time is changed by introducing a new time variable, say $t' = nt$, it is seen that equation 10 will remain invariant if the coefficient P_j is increased in proportion to n^2 and the coefficient P_d in proportion to n. In this way, it is possible to regulate the speed of oscillations without changing their geometrical characteristics; this may be of some interest in experimental work.

Supplementary Note

This paper was written originally to discuss the applications (and lack of applications) of dimensional analysis in electrical engineering in the belief that new uses for model experiments might be uncovered by engineers unacquainted with the basic theory. Between the first writing and the revision of the paper several reports of model experiments in the electrical field have appeared. These are listed in the bibliography.[20–23] They represent an answer to the authors' purpose but since it is only a partial answer the original form of the present paper has been retained.

Appendix A

The fundamental electromagnetic equations are

$$\frac{4\pi}{c}\left(J + \frac{\partial D}{\partial t}\right) = \nabla \times H \qquad (11)$$

$$\nabla \cdot D = 4\pi\rho \qquad (12)$$

$$-\frac{1}{c}\frac{\partial B}{\partial t} = \nabla \times E \qquad (13)$$

$$\nabla \cdot B = 0 \qquad (14)$$

$$F = E + \frac{v \times B}{c} \qquad (15)$$

where J is the vector conduction current density ($J = \gamma E$ expresses Ohm's law, γ is the specific conductivity); $D = kE$ is the vector electric flux density, k the dielectric permeability and E the vector electric field intensity; $B = \mu H$ is the vector magnetic flux density; μ the magnetic permeability and H the vector magnetic field strength; ρ is the electric charge density (no relation to the ρ used previously for resistivity), and F is the force on a unit charge moving with vector velocity v.

By taking $\nabla \times$ of equation 11, differentiating equation 12 with respect to t and substituting, using equation 13 also, there may be obtained

$$\frac{4\pi}{c^2}\left(\mu\gamma\frac{\partial H}{\partial t} + k\mu\frac{\partial^2 H}{\partial t^2}\right) = \nabla^2 H \qquad (16)$$

subject to the assumptions that (Ohm's law) $J = \gamma E$ and that k and μ are constants. Since equation 11 is linear, one term of the Fourier series expansion of H as a function of t may be used $H = H'\epsilon^{j\omega t}$ where H' is a function of the space coördinates only, ω is constant, ϵ the base of the natural logarithms and $j \equiv \sqrt{-1}$.

Then

$$\frac{4\pi}{c^2}(j\mu\gamma\omega - \mu k\omega^2)H' = \nabla^2 H' \qquad (17)$$

which gives the magnetic field distribution. Likewise, for the current distribution and for electric field distribution there may be obtained

$$\frac{4\pi}{c^2}(j\mu\gamma\omega - \mu k\omega^2)J' = \nabla^2 J' \qquad (18)$$

and

$$\frac{4\pi}{c^2}(j\mu\gamma\omega - \mu k\omega^2)E' = \nabla^2 E' \qquad (19)$$

which are similar to equation 17. These equations can be solved only in certain simple cases.

Appendix B

Vector Notation. The Gibbs notation is used. Bold-faced symbols denote vectors, the same symbols in italics and not bold-faced denote the magnitude of the vectors. All vectors are space vectors, not vectors representing the complex numbers of a-c circuit theory. The dot product $a \cdot b$ is the same as the scalar or inner product of a and b; the cross product $a \times b$, is the same as the vector or outer product of a and b. The quantity

$$\nabla \equiv i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z}$$

(i, j, k, unit vectors parallel to the axes XYZ of a rectangular coordinate system) is both a vector and a differential operator. $\nabla \times H$ is the cross product of ∇ and H, sometimes called the curl of H; $\nabla \cdot D$ is the dot product of ∇ and D, sometimes called the divergence of D; $\nabla\phi$ where ϕ is a scalar function of x, y, z, t is sometimes called the gradient of ϕ

$$\nabla^2 \equiv \nabla \cdot \nabla \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

References

1. Dimensional Analysis, B. L. Robertson. *Gen. Elec. Rev.*, v. 33, 1930, p. 207–14.
This article is written by an electrical engineer. In common with most discussions in the field, it does not even intimate an application to electrical engineering problems.

2. Skin Effect in Rectangular Conductors, H. C. Forbes and L. J. Gorman. Elec. Engg., v. 52, 1933, p. 636–39.

3. Skin Effect in Conductors of Given Shape, H. B. Dwight. Elec. Engg., v. 52, 1933, p. 724–25.

4. An Introduction to the Theory of Eddy Current Heating (a book), Davis and Burch. Ernst Benn, London, 1933.

5. Dimensional Analysis (a book), P. W. Bridgman. Yale Univ. Press, 1931.

6. The Effect of Displacement Currents on the High Frequency Resistance of Circular Single-Layer Coils, A. J. Palermo. *I.R.E. Proc.*, v. 20, 1932, p. 1807–10.

7. Principia Mathematica (a book), Isaac Newton. 1723, p. 254.

8. Theorie Analytique de la Chaleur (a book), chapter 2, section IX J. Fourier. 1822.

9. On Physically Similar Systems, Illustration of the Use of Dimensional Formulas, E. Buckingham. *Phys. Rev.*, v. 6, 1914, p. 345–76.

10. The Principle of Similitude, Lord Rayleigh. *Nature*, v. 95, 1915, p. 66–8.

11. The Principle of Similitude and the Principle of Dimensional Homogeneity, R. C. Tolman. *Phys. Rev.*, v. 6, 1915, p. 219–33.

12. Über die Dimensionen physikalischer Grossen, C. Runge. *Phys. Zeit.*, v. 17, 1916, p. 202–12.

13. Der Dimensionsbegriff und der analitische Bau physikalischer Gleichungen, T. Ehrenfest-Afanasjewa. *Math. Annalen*, v. 77, 1916, p. 259–76.

14. Physics: The Elements (a book), N. R. Campbell. Chapters 14, 15. Cambridge Univ. Press, 1920.

15. Die Bedingungen der Moglichkeit einer Massbestimmung in einer physikalischen Mannigfaltigkeit und das Prinzip der Ahnlichkeit, F. London. *Phys. Zeit.*, v. 10, 1922, p. 262–68.

16. Zur Theorie der Dimensionen, J. Wallot. *Zeit. f. Phys.*, v. 10, 1922, p. 329–48.

17. Dimensional Analysis, N. Campbell. *Phil. Mag.*, v. 47, 1924, p. 481.

18. Investigation of Antennae by Means of Models, J. Tykocinski-Tykociner. Univ. of Ill. Exp. Station *Bull.*, no. 147, May 25, 1925.

19. The Method of Dimensions (a book), A. W. Potter. E. P. Dutton and Company, 1933.

20. High Frequency Models in Antenna Investigations, G. H. Brown and Ronold King. I.R.E. *Proc.*, v. 22, 1934, p. 457–80.

21. Supersonic Measurement of the Directional Characteristics of Horns, S. Goldman. Acous. Soc. of Am. *Jl.*, v. 5, 1934, p. 181.

22. High Frequency Induction Furnaces (a discussion), H. Poritsky. Elec. Engg., v. 53, 1934, p. 592–3.

23. Conduction of Electricity in Gases (a book), Joseph Slepian. Westinghouse Co., 1933, p. 91 and p. 123–4.

The M.I.T. Power Factor Bridge and Oil Cell

Recent developments in a bridge devised at Massachusetts Institute of Technology for obtaining high-precision power-factor measurements on small oil samples, and the associated oil cell, are described in this paper, and the results of measurements on oil samples are discussed. Several conclusions drawn from the work done at M.I.T. on power factor bridges and measurements are given.

By
J. C. BALSBAUGH
ASSOCIATE A.I.E.E.

N. D. KENNEY
NON-MEMBER

ALFRED HERZENBERG
ASSOCIATE A.I.E.E.

All of Mass. Inst. of Tech., Cambridge

A RESEARCH project on the development of a power factor bridge, test apparatus, and test methods for the power factor measurement of small oil samples has been carried on since June 1930 in the electrical engineering department of the Massachusetts Institute of Technology. This project was conducted with the financial assistance of the Association of Edison Illuminating Companies and the National Electric Light Association, and in coöperation with the cable research subcommittee of the National Electric Light Association, until the dissolution of the National Electric Light Association. While this specific project has been terminated, the study of the general problem of the fundamental properties of insulating oils in particular and insulation in general will be continued in the electrical engineering department of the Massachusetts Institute of Technology.

Full text of a paper presented at the A.I.E.E. North Eastern District meeting, Worcester, Mass., May 16–18, 1934, and recommended for publication by the A.I.E.E. committee on instruments and measurements. Manuscript submitted Dec. 26, 1933; released for publication July 27, 1934.

The authors acknowledge the support and coöperation of the cable research subcommittee of the underground systems committee of the National Electric Light Association, and the assistance of Prof. D. C. Jackson, Dr. W. F. Davidson, and Dr. V. Bush.

A previous paper "A Bridge for Precision Power Factor Measurements on Small Oil Samples," by J. C. Balsbaugh and P. H. Moon (A.I.E.E. Trans., v. 52, 1933, p. 528–35), discussed some of the general problems of power-factor bridge design and bridge measurements. The present paper includes further developments in bridge design, design of oil cells, inherent power factor of oil cells and the power factor measurement of oil samples. The general theory of the bridge, operation of the bridge, and the design of the detecting circuit is given in a companion paper,[1] "Comprehensive Theory of a Power Factor Bridge," by J. C. Balsbaugh and Alfred Herzenberg (*Jl. of the Franklin Institute*, v. 218, 1934, p. 49–97).

General Description of Bridge

The type of bridge which is recommended for high-precision power-factor measurements on small oil samples is shown in Fig. 1. This bridge is of the Schering type with symmetrical low voltage measur-

1. This paper includes the general bridge and shield equations, the calculation of the measured bridge power factor and capacitance, calculation of the sensitivity of the bridge expressed in terms of the minimum detectable changes in power factor and capacitance, a study of the factors affecting the precision and accuracy of the power factor measurements, effect of a shield unbalance on the measured power factor and capacitance by bridge measurements, calculation and measurement of the power factor of an oil sample, and the measurement and evaluation of the power factor of air capacitors.

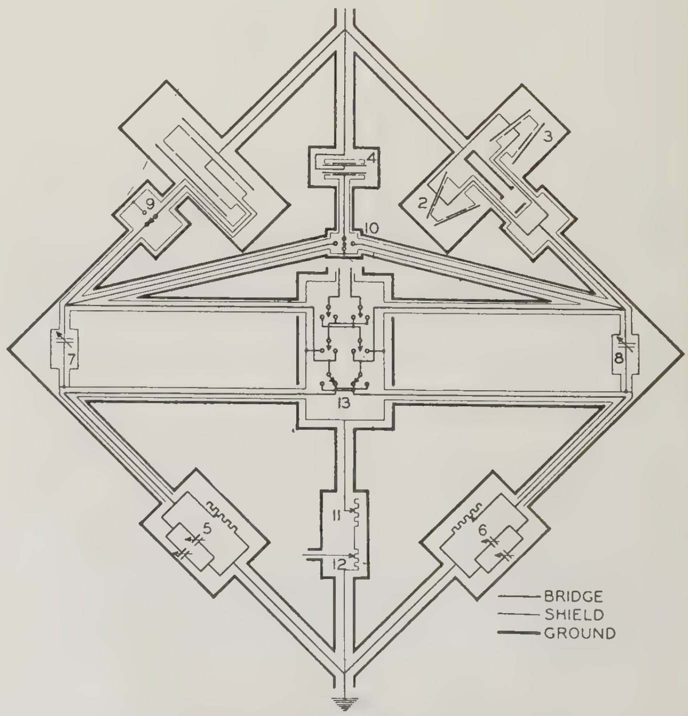


Fig. 1. Diagram of the bridge for high-precision power-factor measurements on small oil samples

ing bridge arms and a variable capacitance in one of the high voltage bridge arms. The bridge is constructed with a single shield circuit so that the effect of a shield unbalance on the measured power factor and capacitance by the bridge may be minimized through adjustment of the capacitance between the shield and either bridge arm.

The component parts of the bridge are indicated in Fig. 1 and may be described as follows:

Item 1. A fixed cylindrical capacitor having a capacitance approximately equal to that of the oil sample.

Item 2. A variable conical capacitor having a maximum capacitance approximately equal to that of the fixed capacitor. This capacitor should be designed so that changes in capacitance of the order of 10^{-4} of the fixed capacitance may be easily obtained.

Item 3. A variable conical capacitor having a total capacitance of the order of 1 to 2 (10^{-12}) farad, a total change in capacitance of approximately 5 (10^{-4}) of the fixed capacitance and designed so that changes in capacitance of the order of 10^{-7} of the fixed capacitance may be obtained.

Item 4. An oil cell for testing an oil sample. The capacitance of this sample with oil should be of approximately the same capacitance as the fixed capacitor. An oil cell having a volume of approximately 50 cu cm of oil and a capacitance of approximately 25 (10^{-12}) farads with oil has been found satisfactory. However, it is possible to decrease these values and still obtain satisfactory measurements.

Items 5 *and* 6. Similar measuring arms consisting of resistance in parallel with variable capacitors. The resistance consists of 1,000, 100, 10, 1, and 0.1-ohm units and has a total resistance of 9,999.9 ohms. The variable capacitors consist of: (1) a variable, 1,500(10^{-12})-farads precision air capacitor through which changes in capacitance of the order of 0.3(10^{-12}) farad can be obtained; and (2) variable mica capacitors having a total range of approximately 300,000(10^{-12}) farads through which changes in capacitance of approximately 1,500(10^{-12}) farads can be obtained.

Items 7 *and* 8. Variable capacitors with a range in capacitance of approximately 2,000(10^{-12}) farads and which may be easily adjusted through a range of approximately 25 (10^{-12}) farads. These capacitors are used for obtaining approximate equality of the capacitances between bridge and shield on the 2 sides of the bridge.

Item 9. Switching arrangement so that the fixed capacitor may be connected to either bridge or to shield.

Item 10. Switching arrangement so that the oil cell may be substituted for the fixed capacitor, connected in parallel with variable capacitors (items 2 and 3) or connected to shield.

Item 11. Resistance for balancing shield. This resistance gives principally magnitude balancing for the shield circuit and should be similar to resistances in the low voltage measuring bridge arms (items 5 and 6).

Item 12. Resistance for phase balancing of the shield circuit. This resistance is approximately 5 ohms, adjustable through 0.1-ohm steps and is connected to give a component of the applied bridge voltage.

Item 13. Switch box consisting of: (1) a switch for reversing the arms of the bridge, that is, to permit item 5 or 6 to be connected to either item 1 or item 2; (2) a switch for connecting the detecting circuit between the bridge arms for bridge balancing and between either bridge arm and shield for shield balancing; (3) a switch enabling the detecting circuit to be reversed.

The switches referred to in the foregoing should be constructed so that the circuit is not broken in making a change in the circuit connections. When a bridge is to be operated with a relatively high applied voltage it is advisable to protect the operator from high voltages on the circuits having normally low voltages and which may be produced by either an open circuit or by a mechanical failure of one of the capacitors (items 1, 2, and 3 in Fig. 1). This may be conveniently accomplished through the use of a voltage regulator type of vacuum tube which breaks down at a relatively low voltage. Two of these tubes may be connected in parallel (back to back) to limit the voltage for each half-cycle. Complete protection of the bridge and shield circuits may be obtained by placing such tubes between each bridge arm and shield and between shield and ground. For a bridge with relatively low capacitances in the high voltage arms, these tubes will carry for a sufficient length of time the full short-circuit current of a power transformer having the required volt-ampere rating to energize the bridge.

The bridge shown in Fig. 1 is shielded at both shield and ground potentials. The use of a shield permits obtaining an approximately uniform gradient over the bridge sections of the oil cell and high voltage capacitors, and also permits power factor and capacitance measurements to be obtained in terms of constants which may be accurately determined. The use of a shield at ground potential for the shield circuit effectively eliminates electrostatic pick-up in the shield circuit and thereby gives a more steady shield balance.

Fixed and Variable High Voltage Capacitors

The design of the fixed capacitor is shown in Fig. 2. This capacitor is of the cylindrical type and consists of high-voltage, bridge, shield, and ground sections supported by a hollow shaft. The component parts of this capacitor are also indicated and explained in Fig. 2.

In this capacitor, insulation is placed between the high voltage section and ground, between shield and

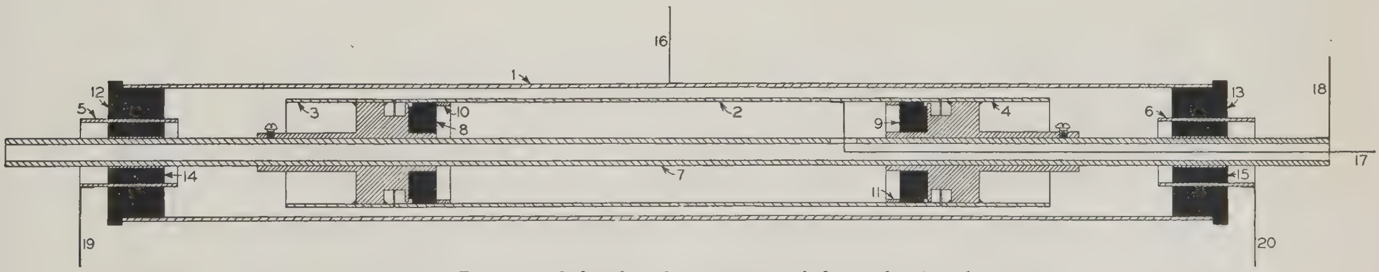


Fig. 2. Design of the fixed capacitor of the cylindrical type

1. High voltage section
2. Bridge section
3, 4. Shield sections
5, 6. Ground sections
7. Shield supporting shaft
8, 9. Insulation between bridge and shield section
10, 11. Spacers for 3, 4 and 8, 9
12, 13. Insulation between high voltage section and ground
14, 15. Insulation between shield and ground
16. High voltage lead
17. Bridge lead
18. Shield lead
19, 20. Ground leads

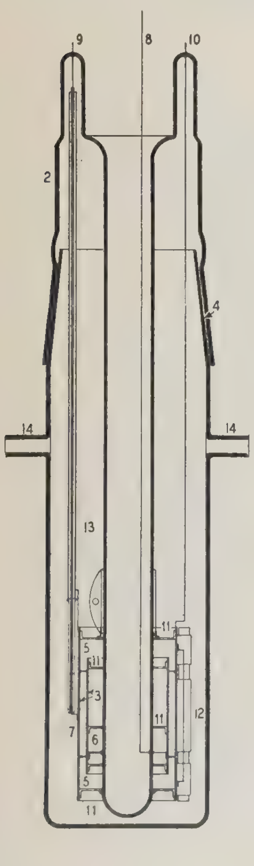
ground, and between the shield and measuring sections. Placing the ground section between the high voltage section and shield prevents variable surface leakage and conduction currents through the insulating support of the high voltage section from giving an unsteady shield balance. It is important that the insulation between bridge and shield sections be shielded from the high voltage section to prevent any loss entering the bridge from this source. Since for bridge and shield balance, the bridge and shield potentials are adjusted to be very closely equal (within the sensitivity of the bridge), the loss in the insulation between bridge and shield will be negligible. It can be shown theoretically that even if the insulation between bridge and shield has a relatively high power factor, the shield may be easily balanced sufficiently closely to prevent any inaccuracies (in the desired range) in the bridge measurements. This fact may also be checked experimentally by balancing the bridge and shield with and without a definite resistance connected between bridge and shield. The insulation used in the construction of this capacitor may be fiber, hard rubber, bakelite, or other similar materials.

The design of the variable capacitors (items 2 and 3 in Fig. 1) is, in general, similar in principle to the fixed capacitor (Fig. 2) but they are conical in shape instead of cylindrical.

Tests have shown that air capacitors may have inherent power factors which may be relatively high in the 0.000001 range. Since a bridge in general measures the difference in power factor of the 2 impedances in the high voltage bridge arms, the measurement of the power factor of an oil sample in one of the bridge arms to a power factor precision of 0.000001 requires either the evaluation of the power factor of the air capacitors, if they are significant in this power factor range, or a capacitor which has an inherent power factor which is negligible in this power factor range. Power factor tests of air capacitors have shown that the power factor of a capacitor designed similarly to Fig. 2 and constructed with brass surfaces may be made negligible in the 0.000001 range by thoroughly cleaning (removing the surface oxide and cleaning with carbon tetrachloride) the measuring surfaces and by operating the capacitors at a gradient of the order of 1,000 volts per inch.

A capacitor of the design shown in Fig. 2 may be constructed from standard tubing. The advantages of this design are: (1) simplicity, (2) the ease of obtaining a shielded lead from measuring section, (3) the ease of disassembling capacitor for purpose of cleaning measuring surfaces, (4) the possibility of using inexpensive types of insulation, and (5) the inexpensive type of construction. Capacitors of the design shown in Fig. 2 have been found satisfactory for high-precision power-factor measurements of small oil samples.

It has been found important to have good connections (the equivalent of soldered connections) for the leads to the high-voltage, bridge, shield, and ground sections of the capacitors. Due to the relatively small currents flowing through these contacts, a poor contact may give a relatively high resistance in addition to producing an unsteady balance.



1. Pyrex glass container for oil sample
2. Pyrex glass cap and supporting tube for cell measuring and shield sections
3. Electrical measuring surfaces of cell
4. Ground joint
5. Shield sections—nickel cylinders
6. High voltage section—nickel cylinder
7. Measuring section—nickel cylinder
8. Lead to high voltage section
9. Lead to bridge section
10. Lead to shield sections
11. Supporting disks—nickel, spot welded to cylinders
12. Supports for 5 and 7—nickel bands and pyrex glass rods
13. Shield for measuring section lead
14. Tubulations for evacuating cell or for permitting sample to be placed in cell. External shield for cell measuring section is placed outside of cell

Fig. 3. Assembly of one type of oil cell for the measurement of the power factor of a small oil sample

Oil Cells

An assembly of one of the types of oil cell which may be used for the measurement of the power factor of a small oil sample is shown in Fig. 3. This cell consists essentially of a pyrex glass container for the oil sample, a pyrex glass cap with supporting tube for the electrical measuring surfaces of the cell and the electrical measuring surfaces consisting of high-voltage, shield, and measuring section nickel cylinders.

Another type of cell that has been used for power factor measurements of oil samples is shown in Fig. 4. This cell is, in principle, essentially the same electrically as the cell shown in Fig. 3 with the exception that it has a copper tube sealed into the glass tube through which the measuring or bridge lead is brought out of the cell. Since the high voltage lead and the bridge lead are necessarily sealed into the glass containing the electrical measuring surfaces, there will be 2 parallel paths from the high voltage section to the measuring section: one directly between the high voltage and measuring-section cylinders and the other through the glass between the high voltage lead and the measuring leads. Thus the measured bridge power factor would include any losses present in both of these paths. The use of a copper tube as shown in Fig. 4 will permit determining the effect of the parallel path through the glass to the measuring lead on the measured power factor by the bridge. The effect of any loss in the glass may be completely eliminated from the measured bridge power factor by connecting the copper

1. High voltage section
2, 4, 5. Shield sections
3. Measuring section
6–12. Supporting disks
13–18. Assembly and supports for 2, 3, 4
19. Clamp for fastening assembly of 2, 3, 4
20. Support for 1
21. Lead to high voltage section
22. Lead to shield
23. Lead to measuring section
24. Copper tube sealed in tube for measuring section lead
25. Lead to copper tube shield
26, 27. Shields for lead to measuring section
28. Pyrex glass insulation between measuring section lead and shield
29, 30. Ground shields
31. Insulation, high voltage to ground
32, 33, 34. Tubulations
35, 36. Pyrex glass cylinders
37. Pyrex glass tube for copper tube and measuring lead

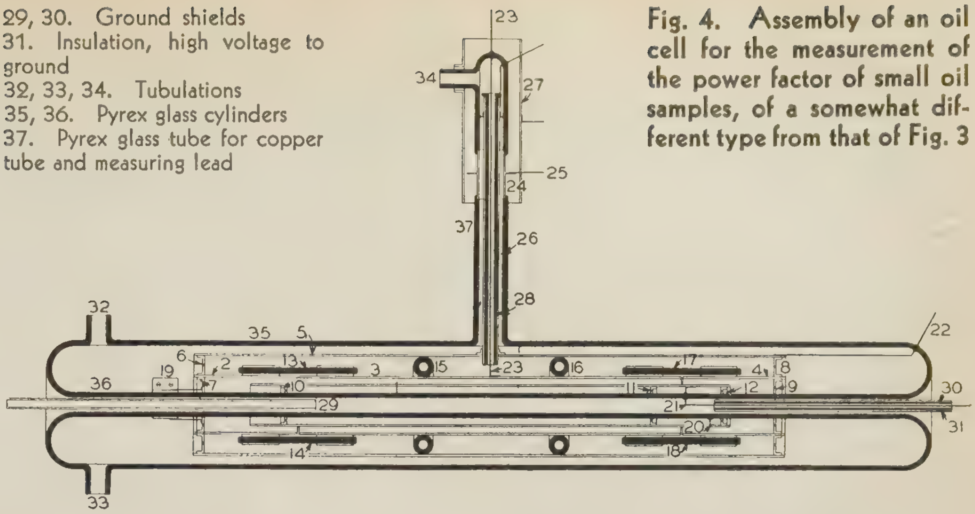


Fig. 4. Assembly of an oil cell for the measurement of the power factor of small oil samples, of a somewhat different type from that of Fig. 3

tube to shield. For this condition any loss in the glass will simply affect the shield circuit balance. With the copper tube connected to the bridge lead a part of the loss in the glass will be measured by the bridge. It has been found that with cell constructions similar to those shown in Figs. 3 and 4, and with a relatively long distance between high voltage and bridge leads, the loss in the glass (with copper tube eliminated from the cell or with the copper tube connected to bridge) will not be significant in the 0.000001 range of measured bridge power factors for temperatures of the cell up to 100 deg C.

The cell shown in Fig. 4 has the bridge section of the cell shielded by means of a nickel cylinder within the cell. For the cell shown in Fig. 3 it is assumed that a satisfactory shield for the bridge section of the cell is provided external to cell. This may conveniently be an external shield at a relatively small distance from the cell with the cell and shield placed in a conducting bath (may be same as heating bath) or a type of shield that may be placed directly on the exterior of the cell (these shields being of sufficient size to shield completely the bottom of cell to a height at least comparable to the interior measuring surfaces).

A cell of the type shown in Fig. 4 may be operated satisfactorily at higher temperatures than the cell shown in Fig. 3 and also may be more easily constructed with a larger capacitance and for larger oil volumes than the cell shown in Fig. 3. Furthermore, a cell of the type shown in Fig. 4 may be completely immersed in an oil bath or placed in an oven (for measurement of power factors at temperatures exceeding room temperatures), whereas the ground joint of the cell in Fig. 3 will limit the permissible cell temperature (particularly so when it is desired to heat the oil under a vacuum), and also will permit only the lower part of the cell to be placed in any oil bath or oven.

The main advantages of the cell construction of Fig. 3 are that the cell may be easily taken apart for effective cleaning following an oil test, and also may be constructed for quite small volumes of oil samples. Where a cell is to be used for testing a number of oil samples, it is desirable to have a relatively simple and effective method of cleaning the cell between tests to prevent contamination of an oil sample from preceding samples. An effective method of cleaning the cell after an oil test has been to remove the cap with the electrical measuring surfaces from the container and thoroughly wash the parts of the cell with carbon tetrachloride and benzene.

A cell of the type of construction indicated in Figs. 3 and 4 also will permit an oil sample to be tested either under a vacuum, that is, excluding air, or in the presence of an inert gas such as carbon-dioxide or nitrogen and thereby prevent contamination of the sample due to contact with air. Testing an oil sample in the presence of an inert gas may also be important in cases where it is desired to test an oil that has been in service, since the testing of the oil under a vacuum may possibly liberate the absorbed gases, thereby producing a change in the oil. The inert gas may be admitted to the cell before the sample is put into the cell, so that any desired pressure comparable to operating conditions may be reproduced for the test sample. Where it is desired to make tests of oil samples from cables in service, the oil may be transferred directly from the cable to the cell in the field, thereby preventing a change in the test sample either due to contact with air or through successive handling of the sample in several containers.

Power Factor Tests of an Oil Cell Before Admission of Oil

Tests have shown that air capacitors may have inherent power factors that may be quite substantial in the 0.000001 range. It is therefore pertinent to investigate the power factor of an oil cell before the admission of oil, and determine the magnitude of this power factor and the methods by which it may be reduced or made negligible in the desired range of power factor measurements. The power factor of the cell before admission of oil to the cell may affect the measured power factor of an oil sample in the cell and the condition producing an inherent power factor may also cause a deterioration of the sample.

Power factor tests on oil cells before the admission of oil are given in Figs. 5 and 6. The cells used for

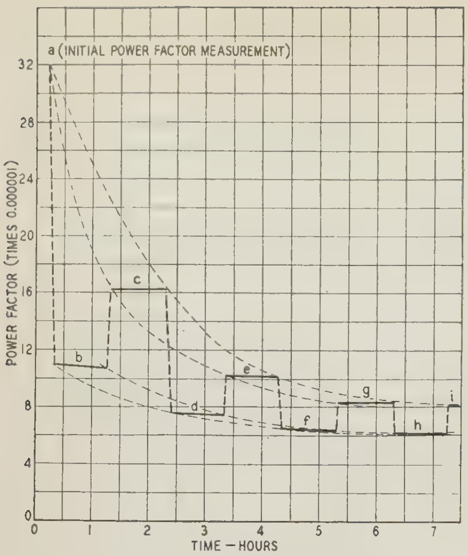


Fig. 5. Power factor tests of an oil cell before admission of oil

a, c, e, g, and i. Power factor measurements at atmospheric pressure (room air)

b, d, f, and h. Power factor measurements at vacuum

All measurements at normal room temperature

these tests were similar in construction to the cell shown in Fig. 4 and as described under the previous heading "Oil Cells." The metal cylinders and disks of the cells were made from a high grade of nickel tubing and nickel strip, respectively, and before assembling in the cells were polished, cleaned with carbon tetrachloride, and then heated in a hydrogen oven at 1,300 deg F for 10 min. Following the construction of the completed cell, the cell was cleaned with carbon tetrachloride and benzene. The tests were made with an average potential gradient of approximately 12,800 volts per inch on the measuring surfaces of the cell and with an applied bridge voltage having a frequency of 55 cycles per second.

Power factor test results are shown in Fig. 5, the measurements being made both at room temperature with room air at atmospheric pressure in the cell and with the cell evacuated (0.0001 to 0.001 mm of mercury). Successive test results in Fig. 5 are indicated by *a*, *b*, etc., to and including *i*, with *a*, *c*, *e*, *g*, and *i* representing measurements with room air at atmospheric pressure and *b*, *d*, *f*, and *h* representing measurements with the cell evacuated. The results given are average values from similar tests made on 6 different cells. Before any power factor measurements were made on a cell it was first sealed to a vacuum system. Following this, the initial power factor of the cell with room air at atmospheric pressure would be either of the order of 0.00003 or impossible to obtain. However, after evacuating the cell no difficulty would be experienced in obtaining a power factor measurement, and the power factor would be from 0.000010 to 0.000012. It is probable that the high or unattainable initial power factor with room air at atmospheric pressure is caused by moisture in the cell, and which the vacuum removes in part, for no further difficulty would be experienced in obtaining power factor measurements with either air or a vacuum. Succeeding power factor measurements with room air at atmospheric pressure and at a vacuum gave the average results given in Fig. 5. It may be noted that for successive evacuations or the admission of room air at atmospheric pressure, both the difference between the power factors and the power factors at atmospheric pressure and at a vacuum decreased until approximately constant values were obtained. The final constant values could also be obtained by maintaining a vacuum in the cell for a sufficient length of time. The magnitude of the difference between the power factors of the cell with room air at atmospheric pressure and at a vacuum, after constant values of power factors were reached, was approximately 0.000002. This difference in power factor was also measured with the room air admitted to the cell through a filter and a liquid-air trap, and it was found to be approximately 25 per cent less than the foregoing value.

An investigation of the effect of temperature of a cell on the power factor of the cell with the cell at a vacuum (0.0001 to 0.001 mm of mercury) gave the results shown in Fig. 6. These temperatures were measured by thermocouples, the thermocouples being located, (*a*) one over the center of the measuring cylinder, (*b*) one under the center of the high voltage cylinder, and (*c*) one between an inner and the outer shield cylinders. The tests shown in Fig. 6 were made on a cell following an evacuation for a sufficient length of time to give the constant sustained values of power factor shown in Fig. 5. Curves *A*, *B*, and *C* in Fig. 6 give power factor against cell temperature for successive heat runs on the cell with the temperatures increased from room temperature to approximately 220 deg C and then decreased. Curve *A′* is a continuation of curve *A*, but due to the rapidity of change in power factor at the higher values, satisfactory measurements could not be obtained. It is interesting to note that for successive heat runs the power factors decrease (below 180 deg C) for corresponding temperatures. Also the temperature difference at a given power factor, for the loop representing increasing and decreasing temperatures of the heat cycle, decreases for successive heat runs. The loop effect of the curves cannot be due to inaccurate temperature measurements, since the maximum difference in temperature between the thermocouples on opposite sides of the space between measuring surfaces was approxi-

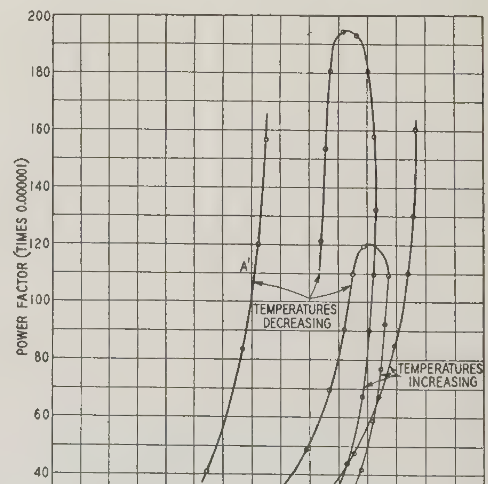


Fig. 6. Power factor tests of an oil cell before admission of oil

Cell under a vacuum

mately 4 deg C. The rate of temperature rise for each of the curves was approximately 30 deg C per hour. The difference in power factors at corresponding temperatures (below 180 deg C) decreased for successive heat runs (with temperature increasing) until continued heating had only a very slight effect on the power factors at a given temperature. For this reason only the results of 3 heat runs are given in Fig. 6. Curve *D* in Fig. 6 gives power factor versus cell temperature after the cell (following the aforementioned heat runs) had been heated by induction until the nickel cylinders of the cell came to a red heat without appreciably changing the degree of vacuum. It is interesting to note that the power factor at 20 deg C decreased to approximately 0.0000005 and, furthermore, was approximately constant through the range of temperature up to 220 deg C. Tests similar to the foregoing were made on a number of cells and substantially the same results as given in Fig. 6 were obtained.

Power Factor Tests on Oil Samples

The results of power factor measurements on a low viscosity type of cable oil (oil that had not been in service) are shown in Fig. 7. The oil used in this test was received from the manufacturer in a metal container which had been throughly cleaned and dried and the air displaced by carbon dioxide before the oil was admitted to the container. After the container was nearly filled with oil the space above the oil was filled with carbon dioxide at a pressure slightly greater than atmospheric pressure. Following this, the container was sealed.

The oil to be tested was transferred from the metal container to a thoroughly cleaned, dried, and evacuated glass flask. This may be done by first pouring a part of the oil into a cleaned funnel connected to the flask through a stopcock. A portion of the oil in the funnel may then be allowed to flow into the evacuated flask. This procedure may be followed until the desired quantity of oil is contained in the flask. The only time that the oil was in contact with air was during the short time of transferring the oil from the metal container to the glass flask.

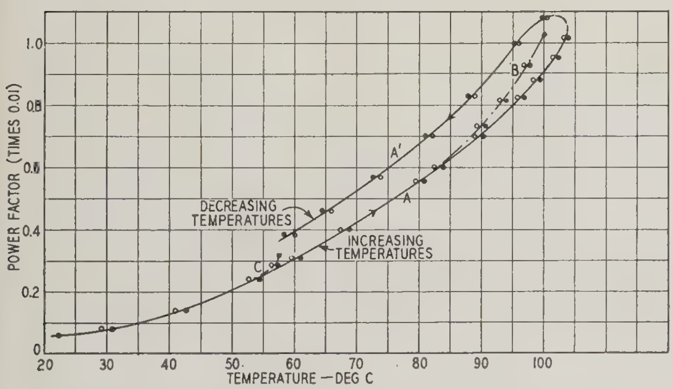


Fig. 7. Power factor measurements on a sample of a low viscosity type of cable oil before being placed in service

Solid dots indicate temperature readings of thermocouple placed directly over center of measuring section
Circles indicate temperature readings of thermocouple placed directly under center of high voltage section

A vacuum was held over the oil in the flask for a period of approximately 3 hr. Then the oil was allowed to flow into another thoroughly cleaned, dried, and evacuated glass flask through a stopcock, the rate of flow of oil being adjusted so that approximately 100 cu cm of oil flowed into the second evacuated glass flask in approximately 6 hr. A vacuum was also held over the oil in the second glass flask. From this flask the oil was allowed to flow into the evacuated oil cell. The foregoing method of treating the oil should permit removing the greater part of the absorbed carbon dioxide from the oil that is admitted to the cell. The stopcocks that were a part of the oil-containing or transfer apparatus were lubricated by the same kind of oil as under test.

The cell used for this test was similar to the cell shown in Fig. 4 with the exception that a copper seal was not used. Oil temperatures were measured by means of thermocouples, one placed directly over the center of the measuring section, another directly under the center of the high voltage section, and another between the inner and outer shield sections. This method permits temperature measurements being obtained inside and outside of the oil under test (that is, the oil between the measuring and high voltage sections). Before the oil was admitted to the cell, the cell was cleaned, evacuated, and heated by induction similarly as for the cell giving curve *D* in Fig. 6 and as explained under the previous heading "Power Factor Tests of an Oil Cell Before Admission of Oil." The power factor of the cell (under vacuum at room temperature) before admission of oil was less than 0.000001 (see Fig. 6).

Measurements on the Oil Sample

After the oil was admitted to the evacuated cell, power factor and temperature measurements were first made at room temperature. All power factor tests given in connection with this group of tests on oil samples were made at a frequency of 55 cycles per second and at an average voltage gradient of approximately 12,800 volts per inch. Then the sample was heated to 100 deg C, first at a rate of approximately 20 deg C per hour from room temperature to 80 deg C, and then at successively lower rates until a constant temperature of 100 deg C was obtained. The sample was maintained at approximately 100 deg C for a period of 2 hr and then was allowed to return to room temperature. This cycle was repeated on one sample 45 times. The results of this series of tests showed that the power factor of the sample (at corresponding temperatures for successive heat runs) decreased at room temperature (approximately 20 deg C) and 100 deg C for the first and second runs, but from the third run on, the power factor of the sample showed no significant average change. The initial power factor at 20 deg C was 0.000875 and the average power factor at 20 deg C for the third and succeeding runs was 0.000562 with a maximum deviation from this value of 0.00005 power factor. The initial power factor at 100 deg C was 0.01125 and the average

power factor at 100 deg C for the third and succeeding runs was 0.01034 with a maximum deviation from this value of 0.00006 power factor. These results were checked with 2 other cells of the same construction using other samples of the same type of oil and with the same test procedure, and gave results substantially the same as the foregoing.

In Fig. 7, curves *A* and *A′* give the power factor of an oil sample for various temperatures from approximately 20 deg C to approximately 100 deg C for increasing and decreasing temperatures. The temperature readings of the thermocouple placed directly over the center of the measuring section and of the thermocouple placed directly under the center of the high voltage section are plotted. Since these thermocouples are symmetrically located with respect to the oil being measured, obviously the average temperature of the oil being measured must closely approximate the average temperature of these 2 thermocouples. This test was made on a sample following the initial decrease in power factor described in the foregoing. The rate of temperature change was approximately 20 deg C per hour for both increasing and decreasing temperatures. It is interesting to note that the power factor of the oil for corresponding temperatures is greater for decreasing temperatures than for increasing temperatures. Furthermore, this phenomenon cannot be explained by erroneous temperature readings, since the difference in average temperature for a given power factor is as large as approximately 8 deg C, whereas the maximum difference between the temperature readings of the 2 thermocouples at any time is approximately 1.5 deg C. Also the power factor at the conclusion of the decreasing temperature part of the cycle returns to the initial reading at room temperature and therefore shows that no progressive deterioration has taken place as a result of the heating cycle. Similar results were obtained on 3 samples of the same kind of oil with similar test conditions.

Curves *A* and *B* give power factor of the sample against temperature, in which the sample is heated to 80 deg C at the same rate as for the foregoing cycle and then the rate is successively decreased until a constant temperature of 100 deg C is reached. It is interesting to note that the power factor for a given temperature changes with a change in the rate of temperature rise and the power factor for a constant temperature of 100 deg C is approximately on the median line of the loop representing the power factors for the increasing-decreasing temperature cycle. Curves *A* and *C* give similar results for a constant temperature of approximately 57 deg C.

Tests on Related Factors

Tests were also made on oil samples to determine the effect of an inherent cell power factor on the measured power factor of an oil sample. For these tests 2 similar cells were used (as shown in Fig. 4 and as described for the preceding tests), one cell being thoroughly cleaned, evacuated, and heated by induction so that the inherent power factor of the cell was negligible in the 0.000001 range of power factor (see Fig. 6, curve *D*), and the other cell being only thoroughly cleaned and evacuated until a constant inherent power factor, 0.000006, was obtained (see Fig. 5, line *h*). These cells were then simultaneously filled with the same type of oil, in a manner similar to the method as given previously. Following this, power factor tests on these samples were made at both room temperature (approximately 20 deg C) and at 100 deg C to determine the difference in power factor of the 2 samples. The kind of oil used for these samples was the same as that used in the preceding tests and gave results substantially the same as those previously given, and also the power factors checked very closely with the values given in Fig. 7. The initial difference in power factor of the 2 samples at room temperature was 0.000017, which decreased to 0.000006 (the same as the initial difference in the inherent power factors of the cell before the admission of oil) after constant power factors at room temperature were reached for both samples. The difference in power factor of the 2 samples at 100 deg C was approximately 0.00058, and this difference was approximately constant and did not change as the power factors of the 2 samples decreased slightly until constant values were obtained (as described previously for the same kind of oil in similar cells). These results show that the inherent power factor of a cell does have an effect on the measured power factor of an oil sample in the cell, but this inherent power factor may be made negligible in the 0.000001 range of power factor.

For the application of an oil cell of the type shown in Fig. 3 for the routine testing of laboratory oil samples or oil samples extracted from cables in service, it is advisable to determine the effectiveness of cleaning the cell following the power-factor measurement of a sample. For this purpose, power factor measurements were made on a number of service-aged oils, the power factor of which varied between 0.0005 and 0.2 at 25 deg C, and between 0.03 and 0.75 at 65 deg C. The cell was cleaned initially and following an oil test, by thoroughly washing the cell with carbon tetrachloride and benzene. Then the cell was connected to a vacuum system and the cell evacuated (approximately 0.001 mm of mercury). The vacuum was maintained on the cell until a constant inherent power factor of the cell was obtained (of the order of 0.000005 to 0.000006). Following this, nitrogen was admitted to the cell to a pressure such that the addition of the oil sample to the cell would give a pressure within the cell of slightly less than atmospheric pressure. Then the oil sample was admitted to the cell. This was accomplished by having an upright tube connected to the cell through a stopcock. The tube was filled with oil and then a portion of this oil was allowed to flow into the cell. This procedure was followed until the desired quantity of oil was contained in the cell. The foregoing method permits heating the oil with air excluded from the cell and also prevents the oil test sample from being injected into a vacuum. The test procedure consisted of first measuring the power factor of the sample at room temperature, then heating the oil to 65 deg C and taking power factor

measurements at this temperature and at intermediate temperatures, and then allowing the temperature of the sample to return to room temperature, and measuring the power factor at room temperature again. The results of these tests showed that for every sample the power factor of the sample at room temperature, following a heat cycle, checked very closely the power factor at the corresponding temperature on the increasing-temperature part of the heat cycle. This indicates that no deterioration of the sample had taken place during the heat cycle. The effectiveness of cleaning the cell was determined by retesting a sample following testing of samples of different oils. In each case it was found that the power factor at both room temperatures and at higher temperatures checked very closely. It is interesting to note that for these service-aged oil samples the power factor at room temperatures did not show the decrease in power factor following a heat cycle as described previously for a different type of oil sample.

Temperature measurements for an oil cell of the type shown in Fig. 3 may be made either by thermocouples located within the cell, or by thermometers located external to the cell. When thermometers are used they may be located, one in the center tube of the cell and filling this tube with oil, and the other external to the cell.

It should be appreciated that in the measurement of the power factor of an oil sample at a given temperature, the precision of power factor measurement may be limited by the precision of temperature measurement. This is, of course, particularly true of power factor measurements made at relatively high temperatures.

Results of Experiences

The following comments are based upon experiences obtained in the development of the apparatus and its use in power factor measurements.

1. Air capacitors may have inherent power factors substantially higher than 0.000001. The magnitude of the power factor depends principally upon the condition of the surfaces and the surface voltage gradients.

2. The air capacitors may be constructed with ordinary insulations. In general the inherent power factor of a correctly designed capacitor will be independent of the power factor of the insulation used in the construction of the capacitor.

3. The use of a bridge with a single shield circuit will permit the bridge and shield balances to be made relatively independent.

4. The measured bridge power factors should be determined in terms of differences in capacitances of the measuring capacitors (items 5 and 6, Fig. 1) for different settings. Such differences may be directly determined from the dimensions of a correctly designed capacitor (conical-type capacitor similar to items 2 and 3, Fig. 1) and correctly connected into the bridge and shield circuits.

5. For high-precision power-factor measurements it is desirable to balance both the bridge and shield to the same precision for both components of balance.

6. The equivalent of soldered or welded connections should be made for leads to the electrical measuring surface of air capacitors and oil cells.

7. An oil test cell may have an inherent power factor which may significantly affect the power factor of a sample measured in the cell, but this inherent power factor may be made negligible in the 0.000001 range by effective cleaning and evacuation.

A Wattmeter for Communication Circuits

An attempt has been made to devise a different type of wattmeter for measuring power and power factor in a-c circuits such as those found in communication service. An adjustable network has been constructed in such a manner that when it is balanced in 3 operations the power factor is indicated directly and the power can be obtained by a short and simple slide-rule calculation.

By
KENNETH R. ELDREDGE*

THERE is a need for a better method of measuring power and power factor in communication circuits, particularly in the laboratory where diversified studies must be made. Ordinary wattmeters are useless because their power requirements are too great. Of course, power measurements can be made with an impedance bridge and thermocouple, or measurements can be made in a given circuit with a power level indicator. Also several vacuum tube wattmeters have been devised. Measurements by these methods are, however, not entirely satisfactory. The impedance bridge method is slow, requires expensive apparatus, and absorbs considerable power from the circuit. The power level indicator must be used in circuits of known constants; then too, frequency changes must be considered. The vacuum tube wattmeters employ special equipment and are somewhat limited in application.

The instrument discussed in this paper has several marked advantages: First, the apparatus comprising the network is inexpensive; second, the measurements are simple compared with existing methods; third, the power factor can be determined without calculation; and last, the power absorption of the wattmeter is small compared with the power levels in the circuit in which it operates. This last is very important. In its present state, however, this instrument also has some disadvantages: (1) There is an appreciable, but not large, frequency error; and (2) The accuracy becomes less at low

A paper recommended for publication by the A.I.E.E. committee on communication. This paper was presented originally before a joint meeting of the Portland Sections of the A.I.E.E. and N.E.L.A., and the A.I.E.E. Oregon State College Branch, Corvallis, Ore., May 21, 1932, and subsequently received honorable mention in the 1932 A.I.E.E. national Branch prize paper competition. Manuscript submitted Dec. 19, 1932; released for publication July 27, 1934.

*Formerly enrolled student A.I.E.E.; paper was prepared while author was a senior student at Oregon State College, Corvallis.

power factors. The range of the instrument is great. With slight modifications it can be adapted to any a-c circuit in which a vacuum tube voltmeter can be made to operate.

In a strict sense, the apparatus is a network in which the elements are balanced with a vacuum tube voltmeter. The connections are such that the phase angle between the voltage and current vectors is readily and directly obtainable; numerical values for the current and voltage are obtained at the same time, and hence the power can be determined by simply computing the product of these 3 measurements.

Method of Making Measurements

In figure 1 are shown the connections of the network used in measuring the power consumed by the load. All the resistors are as purely resistive as possible. Resistor A is a high resistance potentiometer, B is a low resistance potentiometer, and R is a small variable resistor. The voltmeter V is a vacuum tube instrument.

The operation of the circuit is as follows: The contact on A is moved to O and the one on B to M, the electrical center of the potentiometer. The contact on R then is moved to give some arbitrary deflection, e_1, on the voltmeter. After this has been done the contact on B is moved to O, and the one on A is adjusted to give the same voltage, e_2, on the voltmeter. Without disturbing any previous adjustments, the contact on B is moved toward K until the voltmeter again reads the same, e_3. The network now is balanced, and the following theory applies:

If the load voltage be taken as the base, the voltage e_1 (which is half that across potentiometer B) will be at some angle θ as in figure 2. In the second operation the voltage e_2 is made equal to e_1, and it is as shown in figure 2 since it is a portion of the load voltage. In the third operation, by adjusting the contact on B, that is, changing e_1 to some new value e_4, the voltage e_3 measured across the extremities of e_4 and e_2 is made equal to e_2. The vector relations are now as shown in figure 3.

Potentiometer A is calibrated so that its setting a, multiplied by the voltmeter reading e_1, gives the potential in volts across the load. That is,

$$E = ae_1 \tag{1}$$

The load current is measured by the potential drop in the calibrated circuit O-K, consisting of R and B in parallel. Since the

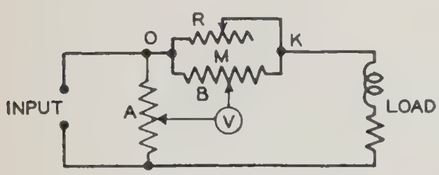


Fig. 1. Schematic diagram of wattmeter circuit

contact on B was set at the electrical center of B, the voltage e_2 is $^1/_2$ of the total voltage drop across the parallel combination, that is $e_2 = Ir/2$, where r represents the resistance in ohms of the parallel resistors R and B. Hence

$$I = \frac{2e_2}{r} \tag{2}$$

The setting, b, of potentiometer B obtained in the third operation gives the load power factor directly as will now be proved. Using figure 3 as a basis, figure 4 has been drawn. Here NP equals PS since the voltages e_2 and e_3 were made equal by adjustment as explained. Let QP be a perpendicular disector of NS. Then angle NQP is a right angle, and NQ is the in-phase component of e_2, or,

$$NP \cos\theta = NQ$$

and

$$\cos\theta = NQ/NP \tag{3}$$

But, NQ equals setting b, divided by 2, that is,

$$NQ = b/2 \tag{4}$$

Also NP equals e_2 which is a constant, or,

$$NP = C \tag{5}$$

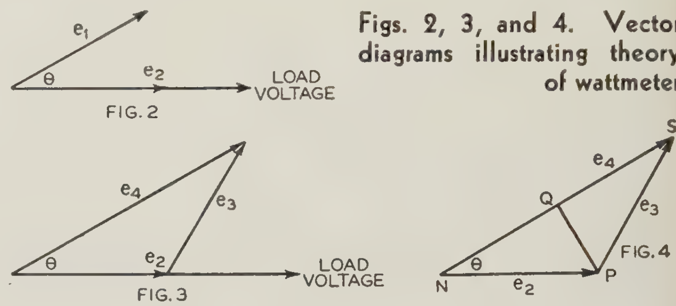
Substituting equations 4 and 5 in 3,

$$\cos\theta = \frac{b/2}{C}$$

and

$$b = C' \cos\theta \tag{6}$$

This last expression is the equation of a straight line, and the power factor is therefore a function of the linear distance along potentiometer B which was calibrated from zero to unity.



Figs. 2, 3, and 4. Vector diagrams illustrating theory of wattmeter

After the separate components of the equation $P = EI \cos\theta$ have been determined, it is only necessary to substitute them in the equation. Thus,

$$P = EI \cos\theta \tag{7}$$

$$P = ae_1 . 2e_2/r . b$$

and

$$P = \frac{2abe_1 e_2}{r} \text{ watts} \tag{8}$$

In actual operation, the values of e_1 and of e_2 were made 10^{-3} volts in all cases. The equation then becomes

$$P = \frac{2ab}{r} 10^{-6} \text{ watts}$$

or

$$P = \frac{2ab}{r} \text{ microwatts} \tag{9}$$

From equation 9 the following factors become available:

1. The power in microwatts is equal to $2ab/r$.
2. The power factor is equal to b.
3. The microvoltamperes are equal to $2a/r$.

From equation 7, other useful factors can be derived. Thus,

$$P = I^2R$$

$$P = IE \cos\theta \tag{7}$$

Then

$$P = I^2 \frac{E \cos\theta}{I}$$

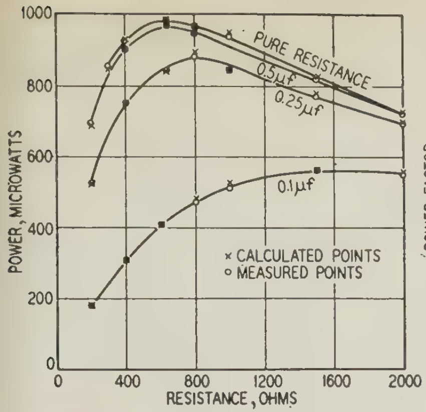


Fig. 5. Power curves with varying resistance and capacitance in series

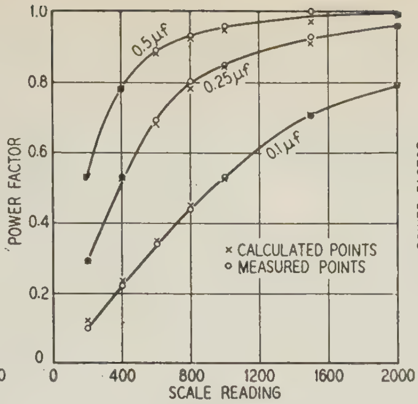


Fig. 6. Power factor curves with varying resistance and capacitance in series

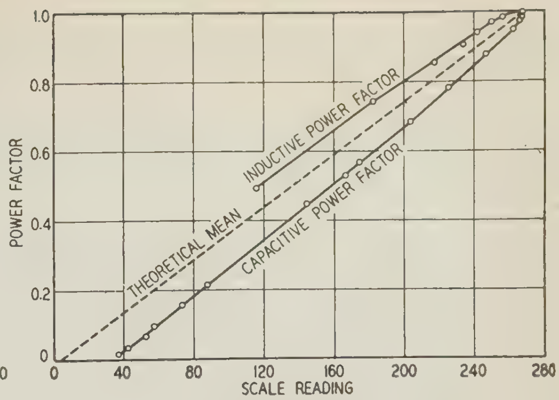


Fig. 7. Calibration curve for potentiometer B

All curves in figures 5, 6, and 7 are for a frequency of 1,000 cycles per second

and therefore,

$$R = \frac{E \cos \theta}{I} \tag{10}$$

Substituting in equation 10 the equations 1, 2, and 6,

$$R = \frac{ae_1br}{2e_2}$$

or, since e_1 equals e_2,

$$R = \frac{arb}{2} \tag{11}$$

Equation 11 then may be broken up as follows:

4. The effective resistance of the load in ohms is equal to $arb/2$.
5. The impedance of the load in ohms is equal to $ar/2$.

These 5 separate terms have been segregated here to show some of the possible applications of the network for determining the specific values of some of the frequently used factors in a-c circuits.

Construction of the Apparatus

For the particular range of currents and voltages that were to be measured in this test, that is, from 10^{-2} to 10^{-4} amperes, and from 0.5 to 2.0 volts at frequencies of from 200 to 3,000 cycles per second, the following apparatus was found to be satisfactory:

1. For the high resistance potentiometer A, a combination of a fixed, noninductive resistor of 200,000 ohms in series with a potentiometer of 600 ohms was used.

2. For B, a small noninductive continuously variable potentiometer of 12 ohms was used.

3. For R, a noninductive continuously variable resistor of about 15 ohms was used. The resistor was calibrated in ohms of resistance while in parallel with the potentiometer B.

4. The vacuum tube voltmeter used was a Western Electric laboratory type instrument with a range of from 3.16×10^{-4} volts to 3.16 volts.

Operating Characteristics

In figures 5 and 6, the data plotted are those of the calculated values of power and power factor and of the measured values of power and power factor. For the most part a very good agreement was obtained. The accuracy is within less than one per cent for high power factors, that is, power factors higher than 0.3. With small power factors, the errors became increasingly greater. This is true for several reasons. As the readings are taken from a calibrated scale, the percentage error of reading increases rapidly at the lower values on the scale. A second reason is that in figure 3, as the power factor angle θ approaches 90 degrees, and e_3 tends toward coincidence with e_2, the precision of setting is smaller as it takes a greater change of e_4 (which is the factor governing b, the power factor setting) to produce a given change of e_3. Satisfactory readings for ordinary purposes, within about 5 per cent can be made with the network at a power factor of 0.1, and for lower power factors approximations down to a power factor of 0.01 are possible.

For some reason the actual power factor of the instrument and the calculated power factor did not agree, that is, the power factor was not exactly a straight line function of the distance along the scale of potentiometer B as theory predicted. On the power factor calibration curve, figure 7, it can be seen that capacitive and inductive power factors fall a slight distance on either side of the theoretical mean. This caused no particular difficulty, but merely necessitated using calibration curves rather than a calculated curve, which, of course, is no limitation.

The apparatus also was tested for frequency error. It was found that calibrations at 1,000 cycles per second were not appreciably in error up to 3,000 cycles per second. At frequencies of less than 500 cycles per second there was an increasing error. This is believed to be caused by 2 factors. At the lower frequencies the probable error of the vacuum tube voltmeter used increases to about 5 per cent. Also, there apparently is among the resistors used, some stray capacitance and inductance which could cause an appreciable frequency error. A second reason for believing this last to be true is that, as already explained, the power factor calibration changes when the load is shifted from capacitive to inductive or *vice versa*.

In operating the instrument for these tests, the power absorption of the wattmeter from the circuit was about 5 microwatts. This loss can be reduced to a small fraction of this value by the use of a higher resistance for A.

Some Characteristics of A-C Conductor Corona

Corona discharges from a-c conductors are characterized by marked polarity effects. The most pronounced electrical polarity effect is the sudden burst of negative corona current each cycle, which sets up high frequency oscillations that produce electromagnetic radiation throughout the radio frequency spectrum. Polished and smooth weathered cables produce such radiation only during negative half cycles; mutilated and contaminated conductors produce it during both positive and negative half cycles under some conditions. An experimental investigation of these effects is described in this paper.

By
F. O. McMILLAN
FELLOW A.I.E.E.

Oregon State College
Corvallis

CERTAIN polarity effects, associated with a-c corona on conductors, have been observed by investigators for many years. Until very recently these polarity phenomena have been of interest almost exclusively because of their fundamental scientific value. Activity in corona research has centered largely about the important problems of determining the laws governing the initial formation of corona and those controlling the power loss resulting from corona. Corona polarity phenomena have not yet been found to be very important factors in either corona formation or power loss; therefore, they have not been investigated actively.

By the use of the synchronous stroboscope Peek[1] observed, during his investigations reported in 1912, a marked difference in the appearance of the positive and negative corona discharges from conductors in a-c corona. He found that the corona discharges around a conductor during a positive half cycle formed a uniform bluish white glow extending to a distance from the conductor which depended on the voltage gradient, curvature of the conductor surface, and the air density. He found the discharges during a negative half cycle to be reddish in color and grouped in tufts or beads that were quite uniform in spacing. These observations quickly were confirmed by other investigators, and now the physical difference in the appearance of the positive and negative corona discharges are known and recognized universally.

In 1913 Bennett[2] observed, during an oscillographic study of a-c corona, a marked difference in the rate of rise of the positive and negative ionization currents. He found that when the critical ionization potential was reached in the half cycle when the conductor was negative, the air around the conductor lost its insulating properties with an explosive suddeness that set up violent oscillations in the electric circuit, unless the circuit contained more than the critical value of resistance. He found the rate of ionization to be much lower, and the tendency to produce electrical oscillations in the circuit very much less in the half cycle when the conductor was positive. Whitehead[3] also has observed that negative corona occurs very abruptly from what he has termed a kind of supersaturated condition. Because of the great difference in the visible appearance of the positive and negative a-c corona on conductors, some distinct and characteristic polarity differences in the electrical phenomena, such as those observed by Bennett and Whitehead, are to be expected.

This paper describes the marked polarity characteristics found during some studies made with the low voltage cathode ray oscillograph of a-c corona on polished, weathered, mutilated, and contaminated conductors, and observations of the electromagnetic radiation produced by the corona discharges in the radio broadcast band of frequencies. A very pronounced electrical polarity effect has been found in a-c corona, which is characterized by a much greater initial rate of change of current during the cyclic bursts of corona current when the conductor is negative than when it is positive. This phenomenon was found to occur on both polished and weathered conductors. This very abrupt burst of negative corona current each cycle initiates high frequency oscillations that produce electromagnetic radiation, or interference, throughout the radio frequency spectrum. The positive corona current, which increases at a much lower rate than the negative, does not produce radio frequency oscillations except under special conditions of conductor contamination or abnormal mutilation.

Bridge for Measuring Corona Current

It can be demonstrated that the dielectric field between 2 identical parallel conductors is undisturbed by the introduction of an infinite conducting plane midway between them if the potential from each conductor to the plane is maintained at half the potential between conductors. Therefore, the dielectric field between a conductor and an infinite conducting plane at a distance $S/2$ from the conductor is exactly similar to half of the field between 2 parallel conductors distance S apart. When the voltage from the conductor to the plane is equal to half the voltage between the parallel conductors, the voltage gradients in the 2 fields are identical. When

Full text of a paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted June 20, 1934; released for publication Sept. 20, 1934.

1. For all numbered references see bibliography at end of paper.

a plane of practical dimensions is used, the field is distorted somewhat, and the total flux is slightly decreased because of the limited area of the plane. The greatest flux distortion occurs near the edges of a limited plane; therefore the use of shielding plates makes it possible to obtain an area near the center of the plane in which the flux distribution is practically the same as in an infinite plane, and when the total neutral plane including the shielding is made large the decrease in the total conductor flux is reduced to a small value.

These fundamental relationships were used to devise a bridge circuit for investigating the corona current on conductors independent of the charging current. The circuit uses the same general principles applied in the bridge circuit developed to study insulator corona and described in a previous paper.[4] The high voltage bridge is shown in Fig. 1. The complete circuit diagram for the bridge with the high voltage testing transformer, the low voltage cathode ray oscillograph, the synchronized sweeping oscillator, and other auxiliary equipment are shown in Fig. 2.

The fundamental principles of operation of the high voltage bridge for measuring corona current are as follows: When capacitances C_1 and C_2 and resistances R_1 and R_2 in Fig. 2 are adjusted to make the potential difference between points A and B zero for some value of voltage less than that required to form corona on the conductor under test, the voltage difference between A and B will remain zero for every other voltage less than the critical corona value. Thus, the charging current is completely balanced out of the cathode ray oscillograph deflection. However, when the voltage on the bridge is increased above the critical corona voltage for the conductor under observation, the current in R_2 is increased by the amount of the corona current, and the voltage drop across R_2 is greater than that across R_1 by the amount of the corona-current voltage drop in R_2. From the value of the resistance R_2 and the voltage sensitivity of the cathode ray oscillograph the corona current calibration readily is calculated for the cathode ray oscillograph deflection. In this investigation the voltage sensitivity of the cathode ray oscillograph was determined, and the resistance R_2 was adjusted to make the current sensitivity 100 μa per centimeter of oscillograph deflection.

In the use of the bridge it was impractical to reduce to a negligible value the stray capacitance to ground of the cathode ray oscillograph with its sweeping oscillator and the necessary batteries. This stray capacitance was between point A of Fig. 2 and ground. In order to balance the bridge perfectly it was necessary to connect a small variable air capacitor C_3 between point B and ground to neutralize the stray capacitance effect.

The high voltage arms of the bridge consisted of the capacitances of 2 conductors 22 ft long to 2 special sheet metal planes. The spacing between each conductor and its plane was made adjustable and entirely independent of the other. The conductor used on the corona-free arm of the bridge was a polished $^1/_2$-in. galvanized iron pipe that had an outside diameter of 0.835 in. after polishing. This conductor was entirely free of corona over the range of spacings and voltages used. The other high voltage arm of the bridge consisted of the capacitance of the conductor under investigation to its neutral plane. The conductors investigated ranged in size from No. 10 A.W.G. copper wire to No. 4/0 aluminum cable steel reinforced. Data for the conductors used are given in detail in Table I.

Each neutral plane was composed of 5 24-gage galvanized-iron plates on $^3/_8$-in. galvanized-iron-pipe frames. The arrangement of plates in the neutral plane for the conductor under investigation is shown in Fig. 1. The neutral plane for the corona-free conductor is directly back of the one shown and identical with it. The plates were supported on oil impregnated maple strips that in turn were supported on lacquered Douglas fir frames. These supports provided excellent insulation for the active sections of the planes and eliminated errors that might otherwise occur in the bridge circuit because of poor insulation. The end plates and the top and bottom plates of the center sections were grounded to form parts of the neutral planes and to shield the active center plates. The flux distribution on these shielded active plates had to approximate that on a segment of an infinite plane having the same size and location, because they are connected to the resistance arms of the bridge as shown in Fig. 2, and because if the dielectric flux distortion is very great the accuracy of the quantitative corona current measurements is reduced.

The effectiveness of the shielding in obtaining the proper flux distribution on the active plates was determined by calculation and experimental measurement. The derivations of the equations are given in the Appendix and the data are tabulated in Table II. Cyclograms were taken of the line voltage and the charging current to the active plates, and the flux terminating on them was calculated from the cyclograms. These experimental data show that, for a spacing of 24 in. from conductor to plane, the active plates intercepted 6.7 per cent more flux than would terminate on a corresponding segment of an infinite neutral plane. These data

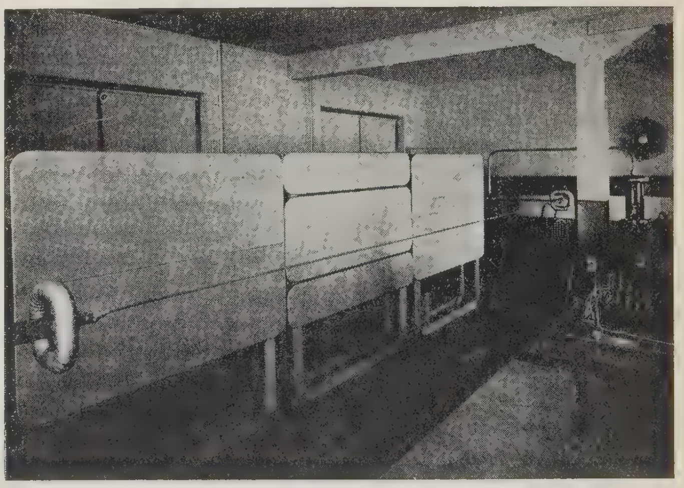


Fig. 1. A high voltage bridge for investigating corona

Table I—Data for Conductors Tested

Conductor	Nominal A.W.G. Size	Number of Strands	Diameter of Strands, Inches	Maximum Diameter, Inches	Condition
Copper wire	10	1	0.099	0.099	Polished
Copper cable	6	7	0.065	0.191	Polished
Copper cable	2/0	7	0.140	0.422	Polished
Copper cable	2/0	7	0.139	0.421	Weathered
Aluminum cable steel reinforced	4/0	7	0.188	0.569	Polished
Aluminum cable steel reinforced	4/0	7	0.189	0.575	Weathered

also show that for this spacing the active plates intercepted 36.1 per cent of the total dielectric flux from the length of conductor opposite them. For the 36-in. conductor-to-plane spacing the flux intercepted by each of the active plates was 11.8 per cent more than that for an equal segment in an infinite plane, and it was equal to 26.7 per cent of the total conductor flux. These experimental data show that the active plates, in the neutral planes that were used, approximate very well the same area in a hypothetical neutral plane midway between 2 parallel conductors, and that by the use of the experimentally determined correction factors, the values of the corona current on conductors can be measured accurately.

The effectiveness of the complete neutral planes, including the active plates, in approximating the conductor flux conditions obtained with 2 parallel conductors spaced distance S apart, was checked by

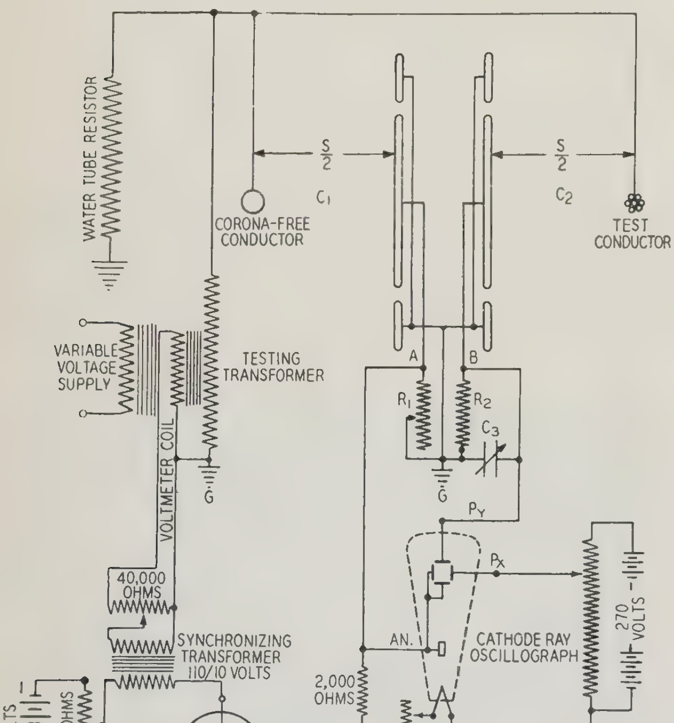


Fig. 2. Circuit for detecting corona formation and measuring corona current on a conductor

determining the visual critical corona voltage for polished wires when they were spaced distance $S/2$ from the neutral planes. The experimental values checked the calculated values very accurately at all spacings, which showed that the neutral planes were satisfactory.

The 2 resistance arms of the bridge were made of identical resistance boxes equipped with wire wound resistance units that could be adjusted for any value of resistance between 0 and 2 megohms. The resistance boxes were specially designed and constructed to secure high insulation and constant resistance with a small time constant.

Voltage Wave Form Correction

When the conductor under test is in corona the initial very high rate of change of corona current each half cycle causes a large instantaneous voltage drop in the transformer reactance and results in an undesirable distortion of wave form in the high voltage output. The most effective way to eliminate this type of distortion is by adding parallel capacitance in the high voltage circuit. Unfortunately, in this investigation it was necessary for the capacitance to be free of corona to avoid extraneous electromagnetic radiation and such a capacitance was not available. Therefore, it was necessary to load the transformer to the point where the instantaneous impedance voltage drop due to corona current was a small part of the total voltage drop in the transformer. The high voltage load was provided by means of a water-tube resistor made up of 2 sections of garden hose connected in parallel electrically and with water circulated through them in series to maintain a constant temperature and a load resistance of one megohm. The point at which the water tube resistance was connected in the circuit is shown in Fig. 2.

Experimental Procedure

Laboratory procedure followed was to string the test conductor in place and then adjust both it and the corona-free conductor to the proper tension and spacing in front of their respective neutral planes. The polished conductors then were treated by first removing all dents and major irregularities with No. 7/0 sandpaper; this operation was followed by the necessary number of applications of a commercial liquid metal polish and vigorous rubbing with cloths and brushing in the case of stranded conductors to give the conductor a high polish. These preliminary operations were followed by polishing with tissue paper and finally with chamois skin to remove all lint and foreign matter from the conductor surface. Special care was exercised to avoid touching or contaminating a conductor in any way after it was polished. Obviously, these polished conductors do not represent a practical service condition, because a few hours' exposure in the laboratory was sufficient to change the corona characteristics to some extent; however, they do establish a standard of comparison for weathered, mutilated, or contaminated conductors. The weathered conductors were not prepared

in any way except that it was necessary to remove from one conductor one or 2 sharp projections caused by abrasion received in rough handling and not in any way related to weathering.

After a conductor was strung in place and prepared for test, the visual critical corona voltage was determined by observation in a darkened room. This voltage was quite definite and critical for polished conductors, but not for the weathered conductors. On weathered conductors corona first appeared in local spots, then distributed along the conductor, and finally developed into general corona.

At a voltage slightly less than the visual critical corona formation value the resistances and capacitances of the bridge were adjusted to balance out the conductor charging current. After the balancing adjustments were made, a series of cathode ray oscillograms and one of cyclograms were taken of the conductor corona current over a range of voltage from slightly less than the visual critical corona value to 110 kv at intervals of 5 or 10 kv as the conditions required.

After the cathode ray oscillograms and cyclograms of the corona current were completed, the conditions were kept the same and a series of Duddell type oscillograms were taken. These oscillograms recorded simultaneously the voltage between the conductor and plane and the audio frequency output of the superheterodyne radio receiver in a field strength measuring set picking up the 1000-kc electromagnetic radiation produced by the conductor corona. The receiver loop was kept in a fixed relation to the high voltage circuit, and the gain in the receiver was maintained constant for all of the tests to make the results comparable.

During the investigation 2 conductor-to-plane spacings, 24 and 36 in., were used. These spacings correspond with conductor-to-conductor spacings of 48 and 72 in., respectively. The apparatus and experimental methods used made it possible to observe visually the characteristics of conductor corona phenomena and the radio frequency electromagnetic radiations caused by corona, and to record them photographically in the form of oscillograms and cyclograms.

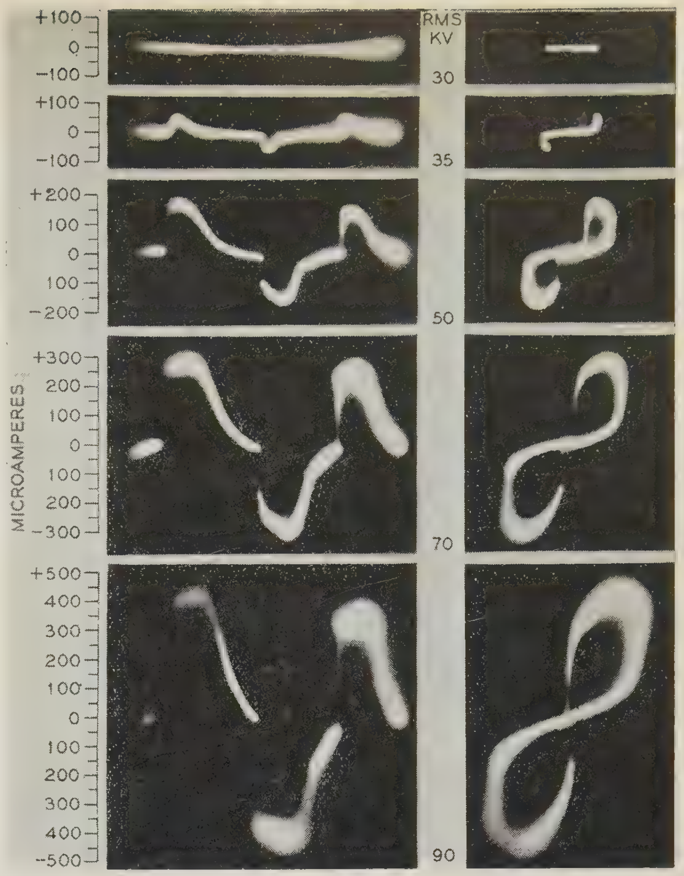


Fig. 3. Cathode ray oscillograms and cyclograms of corona current for a No. 10 polished copper wire

Spacing of conductor from neutral plane, 24 in. Barometric pressure, 751.8 mm of mercury. Temperature: dry bulb 21.7 deg C; wet bulb 15.5 deg C. Humidity: relative, 52 per cent; absolute, 10.25 g per cu m

Polished Conductors

The cathode ray oscillograms and cyclograms in Fig. 3 show the 60-cycle corona current for a No. 10 polished copper wire spaced 24 in. from a grounded plane at various conductor-to-plane voltages ranging from 30 to 90 kv, inclusive. As indicated on the

Table II—Corona Current Correction Factor Data

Conductor: Size A.W.G.	Conductor: Size Diameter, Inches	Conductor: Material	Spacing to Plane, Inches	Conductor Capacitance, $\mu\mu$ F per Foot Calculated From Dimensions: To Infinite Plane	Conductor Capacitance: To Infinite Plane Segment Equal to Active Section of Test Plane	Calculated Per Cent of Total Flux That Would Terminate on Infinite Plane Segment	Actual Conductor Capacitance $\mu\mu$ F per Foot From Experimental Data	Actual Per Cent of Total Flux That Terminated on Active Section of Test Plane
10	0.099	Copper	24	2.46	0.834	33.90	0.882	35.9
6	0.191	Copper	24	2.72	0.921	33.85	0.974	35.8
00	0.422	Copper	24	3.12	1.057	33.88	1.139	36.5
0000	0.565	Aluminum	24	3.30	1.116	33.82	1.197	36.3
								Avg. 36.1
10	0.099	Copper	36	2.32	0.554	23.9	0.628	27.1
6	0.191	Copper	36	2.56	0.609	23.8	0.687	26.8
00	0.422	Copper	36	2.88	0.687	23.8	0.755	26.2
0000	0.565	Aluminum	36	3.06	0.728	23.8	0.814	26.6
								Avg. 26.7

Correction factor for converting the total corona current indicated by the oscillograph to current per foot of conductor = 0.417 for $S/2$ = 24 in.; for $S/2$ = 36 in., correction factor = 0.564.

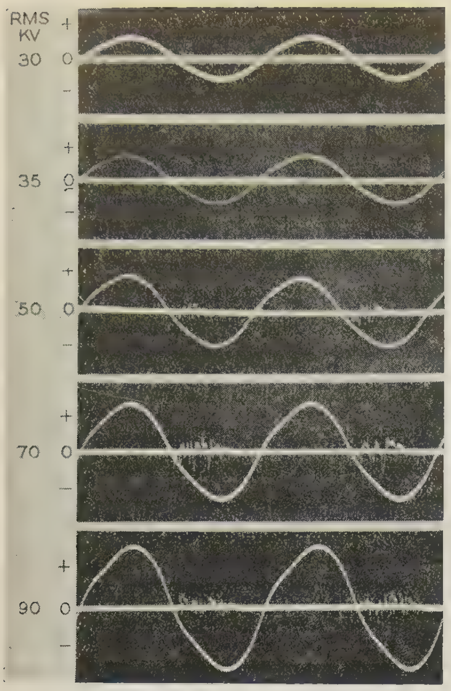


Fig. 4. Oscillograms of conductor-to-plane voltage and radio interference produced by conductor corona on No. 10 polished copper wire

Spacing of conductor from neutral plane, 24 in. Barometric pressure, 750.8 mm of mercury. Temperature: dry bulb 22.2 deg C; wet bulb 15.5 deg C, Humidity: relative. 49 per cent; absolute, 9.55 g per cu m

figure, the deflections above zero are produced by the corona current that flows when the conductor is positive and those below zero when it is negative with respect to the plane. The oscillograms on the left side of the figure have a time scale that was produced by the "trionode" oscillator.[5] The circuit for this oscillator and the method used for holding it in synchronism with the conductor voltage is shown in Fig. 2. The cyclograms on the right side of Fig. 3 were made by applying a voltage proportional to the instantaneous conductor-to-plane voltage on the plates that produced the horizontal deflections,[6,7] and a voltage from the bridge circuit proportional to the instantaneous corona current on the deflector plates that produced the vertical deflections. The horizontal deflections to the right of the center of the cyclograms were produced by positive and those to the left by negative conductor potentials. Zero conductor-to-plane voltage is shown at the center of the cyclogram, and maximum positive and maximum negative voltages are shown at the extreme right and extreme left, respectively. The corona current calibration and the polarity were kept the same for both the oscillograms and cyclograms. The polarities used on the cathode ray oscillograph deflector plates caused the cathode beam to trace the cyclograms in a clockwise direction. Oscillograms and cyclograms both furnish important data that are needed in the study of the characteristics of corona. Oscillograms show the wave form of the corona current directly in rectangular coördinates, and the cyclograms show the phase relation between the conductor-to-plane voltage and the corona current.

An examination of the oscillograms in Fig. 3 shows that the initial corona current increase is very sudden when the corona forms each half cycle because the fronts of the corona current waves are practically vertical. A closer examination shows that the front of the negative corona current wave is much more abrupt than the front of the positive wave. This is shown quite well in both the oscillograms and cyclograms by the fact that the negative corona current rises so rapidly that it does not record on the photographic film until it reaches a considerable value, while the positive current makes a faint trace in practically every instance. This indicates a large difference in the initial rate of change of corona current for the positive and negative waves.

Visual observation of the corona current waves on the fluorescent screen of the oscillograph showed much more detail than could be photographed. These observations showed that the positive corona current wave was quite smooth and free from oscillations, while the negative wave was irregular because of small-amplitude high-frequency oscillations. The photographic records indicate the very abrupt wave front of the negative current, but they do not show the oscillations. These photographic images are in reality smoothed curves for even when the high frequency oscillations were quite pronounced they did not show photographically because approximately $^1/_2$-sec exposure was required and because the nature of corona is such that successive waves are not identical; therefore, the composite image formed by superimposing approximately 30 cycles with small random irregularities was a smoothed curve.

The marked difference observed in the positive and negative corona current is in agreement with the findings of Bennett[2] and Whitehead,[3] and it is further very definitely confirmed by the electromagnetic radiation from the circuit. A series of Duddell oscillograms of the conductor-to-plane

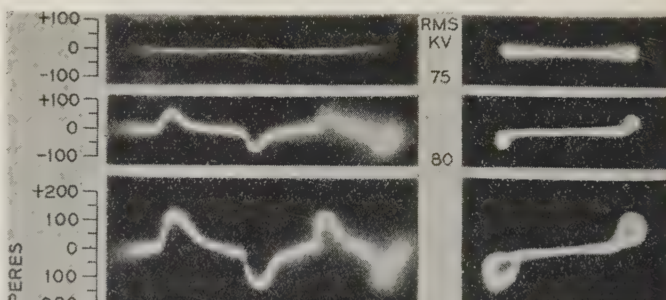


Fig. 5. Cathode ray oscillograms and cyclograms of corona current for a No. 2/0 7-strand polished copper cable

Spacing of conductor from neutral plane, 36 in. Barometric pressure, 757.5 mm of mercury. Temperature: dry bulb, 21.1 deg C; wet bulb 13.9 deg C. Humidity: relative, 44 per cent; absolute, 8.01 g per cu m

voltage and the audio frequency output of the superheterodyne receiver in the field strength measuring set, tuned for 1,000 kc, are shown in Fig. 4. These oscillograms are for the No. 10 polished copper wire, and the conditions are the same as they were when the cathode ray oscillograms and cyclograms of Fig. 3 were taken. The oscillograms in Fig. 4 show that positive corona on the conductor did not produce any 1,000-kc radiation, but that the negative corona produced radiation every negative half cycle when the conductor voltage was above the visual critical corona value. It may be observed that the interference from negative corona starts at the first burst of corona each negative half cycle and stops quite abruptly when the crest of the voltage wave on the conductor is reached.

The cyclograms in Fig. 3 and the oscillograms in Fig. 4 show very clearly how the instantaneous corona formation voltage decreases and passes through zero as the effective value of voltage on the conductor is increased above the visual critical value. At 35 kv (rms) corona occurred practically at the crests of the voltage waves, at 70 kv, the instantaneous corona formation voltage was almost zero; and at 90 kv, the instantaneous conductor voltage had not reversed when corona formed for the succeeding half cycle. This is conclusive evidence that at voltages in excess of the corona value, powerful space charges are produced that are large enough to cause ionizing gradients about conductors when the instantaneous conductor voltage is zero or even in opposition.

The oscillograms and cyclograms in Figs. 5 and 6 are for a No. 2/0 7-strand polished copper cable spaced 36 in. from the grounded plane. A study of these oscillograms shows that the fundamental characteristics are very much the same as those observed on the No. 10 polished copper wire. Voltage

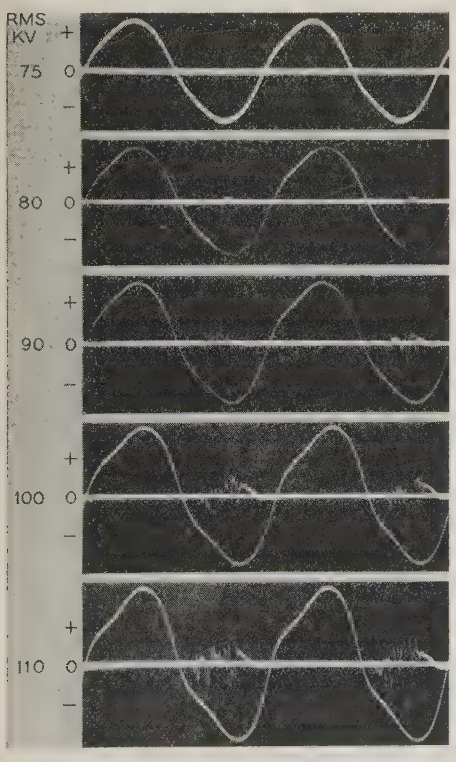


Fig. 6. Oscillograms of conductor-to-plane voltage and radio interference produced by conductor corona on a No. 2/0 7-strand polished copper cable

Spacing of conductor from neutral plane, 36 in. Barometric pressure, 759.6 mm of mercury. Temperature: dry bulb 19.7 deg C; wet bulb 12.8 deg C. Humidity: relative, 43 per cent; absolute, 7.22 g per cu m

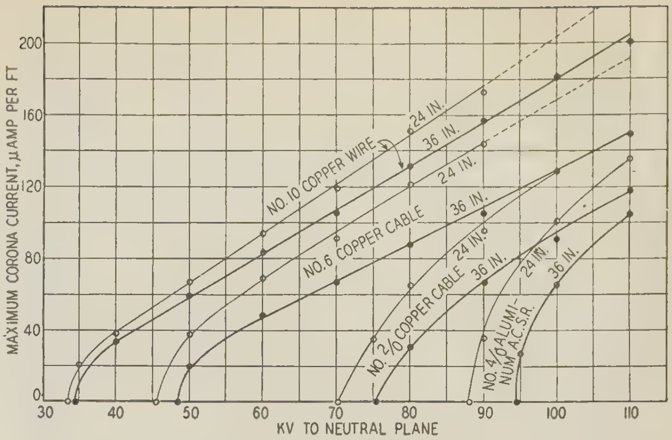


Fig. 7. Maximum corona current per foot of conductor; all conductors polished

Designations on curves indicate conductor-to-neutral spacing in inches

limitations of the testing transformer prevented carrying the tests on the large conductors to twice the visual critical corona voltage, as was done with the No. 10 conductor; however, the tests were carried to voltages far in excess of any practical operating condition in every instance. Cyclograms and Duddell oscillograms for both copper and steel-reinforced aluminum cables show the characteristic decrease in the instantaneous voltage at which corona forms each half cycle as the effective voltage is increased above the visual critical value. Cathode ray oscillograms and cyclograms show that the initial bursts of corona current are much more abrupt on the negative waves than they are on the positive, and visual observation with the cathode ray oscillograph showed superimposed oscillations on the negative waves while the positive waves were smooth. Duddell oscillograms of the radio interference produced by the conductor corona show that interference occurs only when polished cables are negative. These observations on the cables all agree qualitatively with those made on the No. 10 polished copper wire.

Because the fundamental characteristics for all the polished conductors were so much alike, it was thought that the experimental results could be shown clearly by the use of a few typical series of oscillograms and cyclograms on different conductors at the same spacing and by the use of graphs to show some characteristic data for all the conductor sizes and spacings studied. The data selected for graphical presentation were the maximum corona current per foot of conductor as a function of the conductor voltage to neutral. These data were obtained from the cathode ray oscillograms and cyclograms and converted to microamperes per foot of conductor by applying the experimentally determined calibration factors given in Table II.

Maximum corona current per foot of polished conductor as a function of the conductor to plane voltage is shown in Fig. 7 for 24- and 36-in. conductor-to-plane spacings and several different sizes and types of conductors. The intercepts of the curves on the voltage axis are the voltages at which the first visible corona appeared on the various con-

ductors. It should be observed that a slight voltage increase above this initial critical value caused the maximum current to increase very rapidly, then more slowly, and finally, as the voltage was increased further, the current became practically a linear function of the voltage increase over the range investigated. Maximum values of the positive and negative waves were found to be the same within the limits of experimental error, and the points on the curves are the arithmetical mean of the positive and negative measured values. It is interesting to observe that the curves of maximum corona current at various values of conductor-to-plane voltage have the same form as those obtained by Whitehead,[8] for the diameter of corona as a function of the conductor voltage.

The initial abrupt rise of negative corona current per foot of polished conductor as a function of the conductor-to-plane voltage was measured for both the 24- and 36-in. conductor-to-plane spacings and several sizes and types of conductors. These data were found to be more erratic than the maximum corona current shown in Fig. 7; however, they showed the same general relationship to the conductor voltage. This initial abrupt rise, which occurs in the negative corona current and does not occur in the positive, is very significant and important because the very sudden and abrupt change in the circuit stored energy associated with this sudden current change is undoubtedly responsible for setting up local high frequency oscillations that radiate energy at radio frequencies. Data obtained from the oscillograms and cyclograms showed that the magnitude of the initial abrupt rise in the negative corona current increased very rapidly for slight increases in voltage above the visual critical corona value and then became practically a linear function of the voltage for higher values. These data also showed that the initial abrupt increase in negative current is greater for small than for large conductor spacings.

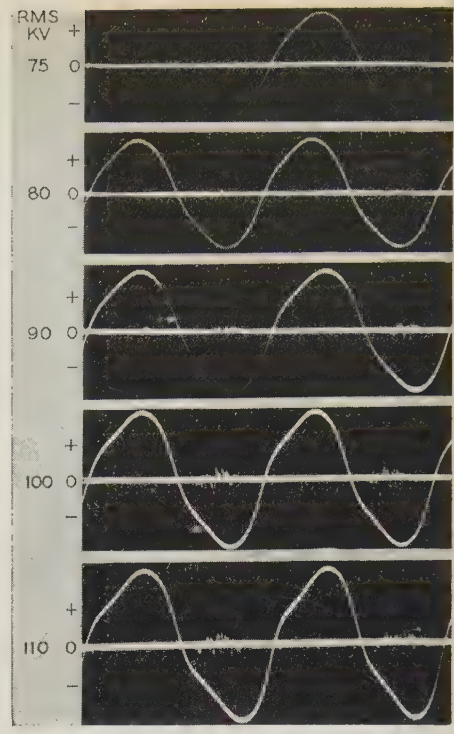


Fig. 9. Oscillograms of conductor-to-plane voltage and radio interference produced by conductor corona on a No. 2/0 7-strand weathered copper cable

Spacing of conductor from neutral plane, 36 in. Barometric pressure 751.7 mm of mercury. Temperature: dry bulb 23.2 deg C; wet bulb 16.6 deg C. Humidity: relative, 50 per cent; absolute, 10.25 g per cu m

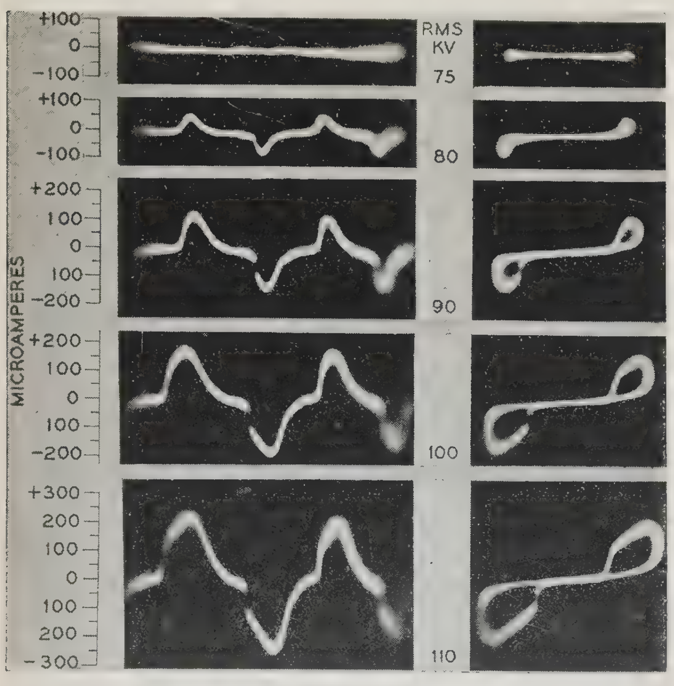


Fig. 8. Cathode ray oscillograms and cyclograms of corona current for a No. 2/0 7-strand weathered copper cable

Spacing of conductor from neutral plane, 36 in. Barometric pressure, 761 mm of mercury. Temperature: dry bulb 20.4 deg C; wet bulb 14.6 deg C. Humidity: relative, 53 per cent; absolute, 9.22 g per cu m

Weathered Conductors

Corona characteristics of weathered conductors are of particular interest because the weathered surface represents the usual condition in service. There are all degrees of weathering, and exposure to the elements in different localities may produce quite varied results because of local conditions. For these reasons, the weathered conductors selected for this investigation were taken from lines that had been in service several years in locations where no abnormal atmospheric contamination, such as smoke, gas, or chemical fumes, existed. The conductors used were free from abnormal abrasions or irregularities because it was desired to determine the influence of weathering alone as far as practicable. Oscillograms and cyclograms were taken for a No. 2/0 7-strand copper conductor and a No. 4/0 aluminum cable steel reinforced to make the data comparable with those taken on polished conductors of the same sizes and materials.

Cathode ray oscillograms and cyclograms of the corona current on the No. 2/0 weathered copper cable are shown in Fig. 8. These oscillograms and cyclograms and those taken for No. 4/0 aluminum cable steel reinforced are practically identical in general shape and character with those shown in Fig. 5 for the No. 2/0 polished copper conductor. All of these oscillographic records show the same characteristic very sudden rise in the negative corona current that was observed for the polished

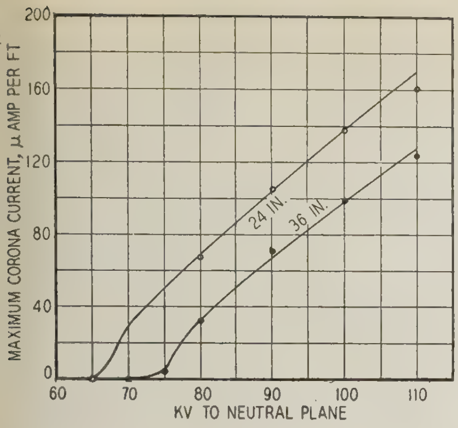


Fig. 10. Maximum corona current per foot of conductor for No. 2/0 weathered copper cable

Designations on curves indicate conductor-to-neutral spacing in inches

conductors, proving that this phenomenon is not attributable entirely to the condition of the conductor surface.

Visual observation in a dark room showed that the corona started on the weathered copper conductor at from 92 to 93 per cent of the voltage required to initiate corona on polished conductor of the same size. These percentages were the same for both the 24- and 36-in. conductor-to-plane spacings.

Dark room observations showed that the corona started on the No. 4/0 weathered aluminum conductor at from 85 to 86 per cent of the voltage required to initiate corona on polished conductor of the same size. These percentages held for both the 24- and 36-in. spacings. The fact that the corona formation voltages on weathered aluminum cable are a smaller percentage of the values for polished cable than were obtained for copper cable should not be considered to indicate any difference in weathering characteristics of copper and aluminum. The weathering results are not comparable, because the weathering conditions to which the cables were subjected were not the same.

On both the copper and aluminum weathered cables the corona first formed in local spots that increased in number as the voltage was increased until the conductors were in general corona. Because of this process of corona formation, the maximum corona current increased very gradually for small increments of voltage above the initial value, then quite rapidly for an interval as general corona was reached, and finally the current became practically a linear function of the voltage. Maximum corona current per foot of conductor as a function of the conductor to plane voltage is shown graphically in Fig. 10 for weathered copper and in Fig. 11 for weathered aluminum cable. For all values of voltage investigated, the maximum corona current for weathered copper cable was somewhat larger than for polished copper; however, on the linear portions of the curves the increase in maximum current was only of the order of 3 to 10 per cent.

Curves of the maximum corona current per foot of conductor for No. 4/0 weathered aluminum cable are shown in Fig. 11. In general, these curves are similar to those obtained for the copper cable if account be taken of the fact that they are for a larger conductor, and that therefore the current will become a linear function of the voltage at a higher conductor-to-plane voltage. Over the range of voltage investigated, the maximum values of corona current for weathered aluminum cable were larger than those for polished cable, except at 110 kv for the 36-in. conductor-to-plane spacing where the current for the polished conductor was slightly larger.

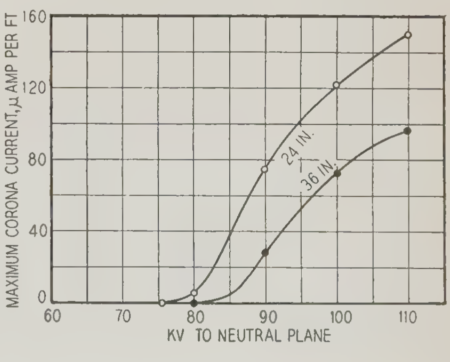
Duddell oscillograms of the voltage and the 1,000-kc electromagnetic radiation or radio interference from the weathered copper conductor are shown in Fig. 9. The oscillograms for both copper and aluminum weathered cables show that in general the characteristics of the radiation are the same as those for polished conductors. The high frequency radiation occurs when the conductor is negative and does not occur when it is positive. Measurements of the field strength of this radiation show that, notwithstanding the fact that the high frequency radiation starts at a lower value of voltage on a weathered conductor than on a polished one, the radiation is greater from the polished conductor, for corresponding values of voltage above the critical corona voltage, than from the weathered conductor. This difference in the intensity of the radiation from polished and weathered conductors shows that, even though the cathode ray oscillograms and cyclograms were not swept at a velocity high enough to show the difference in the rate of rise of the cyclic bursts of negative corona current, the rate of current rise is considerably more rapid for polished than for weathered conductors.

Mutilated Conductors

A study was made of the influence of the surface roughness of conductors on corona and the resulting high frequency electromagnetic radiation. During this work it was found that corona on mutilated conductors having sharp projecting irregularities produced high frequency radiation or radio interference when the conductor was both positive and negative instead of only when the conductor was negative as was found for polished and weathered conductors without abrasions. The positive radiation or interference occurred at a voltage much higher than the visual critical corona voltage, and the voltage at which it appeared decreased as the roughness of the conductor was increased. Radio interference produced by the positive corona on roughened conductors was entirely different from that produced by negative corona. The positive corona produced a single violent impulse in the radio receiver apparently produced by the radiation from a single

Fig. 11. Maximum corona current per foot of conductor for No. 4/0 weathered aluminum cable steel reinforced

Designations on curves indicate conductor-to-neutral spacing in inches



high frequency wave train. Near the voltage at which the positive interference first occurred, there was only an occasional impulse of positive interference; at higher voltage they became regular and one impulse occurred each positive half cycle. At very high voltages relative to the visual critical corona voltage, sometimes 2 or more positive impulses occurred per half cycle; however, they were always distinct impulses with considerable separation. The negative interference always was made up of a rapid succession of impulses that continued from the first burst of negative corona until the crest of the negative voltage wave was reached every negative half cycle, just as had been observed previously for polished and weathered conductors. The only apparent change in the positive corona current wave form during the occurrence of positive interference was the appearance of a superimposed high frequency that could be detected only by visual observation on the fluorescent screen of the cathode ray oscillograph. Photographic records of the cathode ray oscillograms did not show this change.

It was noticed during the study of positive corona interference that when positive interference was occurring only occasionally was there a distinctly audible corona snap coincident with the radio interference observed visually with the Duddell oscillograph. Observation of the conductor with the room darkened, under these conditions, revealed that the positive radio interference was produced by discharges consisting of a small intensely ionized path, extending out a considerable distance from the conductor and terminating in a plume of ionization beyond the normal corona envelope. These plume discharges were of very short duration as shown by their characteristic sharp snap and the character of the radio interference produced.

Contaminated Conductors

New conductors usually have some grease and other foreign matter on them when they leave the factory, and during shipment and erection they may be subjected to further contamination. The influence of this foreign matter on corona formation[9,10] and radio interference is, therefore, of importance during the early life of a transmission line until the contamination is washed or weathered away.

During the early part of the investigation on polished conductors, it was observed, that when potential was applied on a new conductor before it was cleaned and polished, negative followed by positive high-frequency radiation due to corona would occur at comparatively low voltages. Surface contamination on such a conductor may include a great many different kinds of foreign matter. It was known that the surface material on these conductors contained some kind of grease. Therefore, some tests were made with lubricating oil and petrolatum on a clean polished conductor in an attempt to duplicate the observed results.

A cloth saturated with a light high-grade machine oil was wiped over the surface of a polished copper conductor to form a thin oil film over $^1/_2$ its length. This oil film reduced the visual critical corona voltage below that for the dry polished conductor, but it did not produce any positive radio interference even at more than twice the visual critical corona voltage. The other half of the conductor then was greased with a heavy irregular coating of petrolatum. The petrolatum lowered the visual critical corona voltage and produced positive radio interference at a very low voltage. Visual observation with the room darkened showed that positive corona plumes were forming in very large numbers. The thickness of the petrolatum film and the irregularity were reduced by wiping the conductor several successive times, and the effect on the formation of positive corona plumes was observed. Some positive corona plumes continued to form until the conductor was wiped clean with a dry cloth.

Correlation of Results With Corona Theory

In a previous paper[4] a theory was proposed for the phenomena associated with a-c corona formation. This theory has been found to explain in a satisfactory manner the observed positive and negative corona effects and accounts for the experimental fact, revealed by this investigation, that normally only the negative half-wave of a-c conductor corona produces high frequency electromagnetic radiation.

The theory of a-c corona proposed is based upon Townsend's[11] theory of the ionization of gases by collision and the influence of the difference in mobility of the positive and negative ions on the space charges[12,13] surrounding a conductor in a-c corona. The theory is summarized briefly here to show the correlation with experimental observations.

When the instantaneous conductor polarity is positive, ionization starts when the critical ionization voltage gradient is produced by the resultant field of the positive conductor and the positive residual space charge, and continues to the crest of the positive voltage wave. The highly mobile negative electrons and ions are swept from the field and absorbed by the positive conductor leaving in their paths the relatively immobile positive ions that are formed as a result of ionization by collision. These positive ions have on the average a relatively long life, because the negative ions are removed from the field in large numbers by the positive conductor; this reduces the positive ion loss due to recombination, and the low mobility of the positive ions limits their loss by diffusion. The preponderance of positive ions surrounding the conductor produces a positive space charge. This positive space charge persists after the conductor potential reverses to negative polarity, and it plays a very important part in determining the voltage gradient around the conductor during the initial part of the half cycle following its formation.

The most conclusive evidence of the existence of large space charges surrounding conductors in a-c corona is the fact that at effective voltages slightly in excess of twice the visual critical corona voltage the large space charges prevailing will produce ionizing voltage gradients around a conductor when the instantaneous conductor voltage is passing through zero or is in actual opposition to the corona forma-

tion.[14] See the 70- and 90-kv corona-current cyclograms in Fig. 3 for examples of this phenomenon.

When the conductor potential changes to negative polarity, ionization starts when the critical ionization voltage gradient is produced by the resultant field of the negative conductor and the positive residual space charge and continues to the crest of the negative voltage wave. The highly mobile negative electrons and ions are repelled from the negative conductor, leaving in their wakes the relatively immobile positive ions that result from ionization by collision. These positive ions form a positive space charge about the conductor.

It should be observed that a positive space charge is formed adjacent to the conductor regardless of whether the ionization is caused by a positive or negative half cycle of voltage. However, a larger positive space charge is established during a positive half cycle than is produced by a corresponding negative half cycle of voltage. This is because when the conductor is positive the positive space charge flux adds to the conductor field and extends the ionizing gradient, but when the conductor is negative the positive space charge flux subtracts from the conductor field and limits the extent of both the ionizing gradient and the outside corona boundary.

When the conductor voltage reverses and becomes negative following the establishment of a large positive space charge in the manner just described, a very high voltage gradient is produced between the negative conductor and the residual positive space charge because of the very short distance between them. When this voltage gradient reaches the critical ionizing value (which may occur before the voltage actually becomes negative) breakdown occurs probably in the form of minute arcs that neutralize the space charge. These corona arcs produce extremely sudden changes in the energy conditions of the circuit and produce high frequency oscillations of a violent character. When the conductor is positive the positive space charge has the same polarity as the conductor, and there is no opportunity for an extremely sudden energy change to take place that will cause high frequency oscillations. Therefore, when normal polished or weathered surface conditions exist on a conductor that is in a-c corona, high frequency electromagnetic radiation or radio interference will occur only when the instantaneous conductor potential is negative. This theoretical conclusion is in agreement with the experimental results of this investigation.

Summary

1. Some polarity effects in a-c corona have been known and recognized for many years.

2. The most pronounced visible polarity effect is the marked difference in the appearance of the positive and negative corona discharge around a conductor when it is in a-c corona.

3. The most pronounced electrical polarity effect in a-c corona is the very much greater rate at which the corona current increases when the conductor is negative than when it is positive.

4. The sudden burst of negative corona current each cycle sets up high frequency oscillations that produce electromagnetic radiation or interference throughout the radio frequency spectrum.

5. The positive corona current does not produce radio frequency oscillations except under special conditions.

6. Polished conductors in a-c corona radiate radio interference only during the half cycle when the conductor is negative.

7. Smooth weathered conductors in a-c corona radiate radio interference only during the half cycle when the conductor is negative.

8. Mutilated conductors with sharp projections radiate radio interference under some conditions both when the conductor is positive and when it is negative.

9. Petrolatum contamination on conductors causes them to radiate radio interference under some conditions both when the conductor is positive and when it is negative.

10. When electromagnetic radiation occurs from a conductor in a-c corona on both polarities, there is a distinct difference in the positive and negative radiation.

Appendix—Derivation of Equations for Calculating Capacitance Between Conductor and Neutral Plane

Symbols

C = capacitance
ψ = dielectric flux
D = dielectric flux density
A = area
v = velocity of light = 3×10^{10} cm per second
g = potential gradient
k = relative permittivity
x = distance, along neutral plane at right angles to a perpendicular from conductor to neutral plane
a = distance from conductor to point in dielectric field
S = spacing from conductor to image of conductor such that the neutral plane is at distance $S/2$ from conductor
r = radius of conductor
e = voltage (maximum)
e_n = voltage to neutral (maximum)

Equations

The capacitance in any circuit is given by the equation

$$C = \frac{\psi}{e} \tag{1}$$

For any equipotential surface

$$\psi = DA \tag{2}$$

$$= g\,\frac{10^9 k}{4\pi v^2}A \tag{2a}$$

For 1 cm of line the flux through an area of elemental width, dx, is

$$d\psi = g\,\frac{10^9 k dx(1)}{4\pi v^2} \tag{3}$$

It can be shown that when S is large compared with r (see "Dielectric Phenomena in High Voltage Engineering," by F. W. Peek, p. 339) in the neutral plane

$$g = \frac{1}{a^2}\left[\frac{Se_n}{\log_\epsilon\left(\frac{S}{r}\right)}\right] \tag{4}$$

when

$$a^2 = \sqrt{\left(\frac{S}{2}\right)^2 + x^2} \tag{5}$$

Then from eqs 4 and 5

$$g = \left[\frac{Se_n}{\log_\epsilon \frac{S}{r}}\right]\frac{1}{\left(\frac{S}{2}\right)^2 + x^2} \tag{6}$$

and from eqs 3 and 6

$$d\psi = \left(\frac{10^9 k \quad Se_n}{4\pi v^2 \log_\epsilon \frac{S}{r}}\right)\frac{dx}{\left(\frac{S}{2}\right)^2 + x^2} \tag{7}$$

Integrating

$$\psi\Big]_{x_1}^{x_2} = \frac{10^9 k S e_n}{4\pi v^2 \log_\epsilon \frac{S}{r}} \int_{x_1}^{x_2} \frac{dx}{\left(\frac{S}{2}\right)^2 + x^2}$$

$$= \frac{10^9 k e_n}{4\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{2x_2}{S} - \tan^{-1}\frac{2x_1}{S} \right] \qquad (8)$$

From eqs 1 and 8 the capacitance to the neutral plane, between x_1 and x_2

$$C = \frac{10^9 k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{2x_2}{S} - \tan^{-1}\frac{2x_1}{S} \right] \qquad (9)$$

The capacitance between an infinite neutral plane and conductor of radius r at distance $S/2$ from the neutral plane, $x_1 = 0$ and $x_2 = \infty$

$$C = \frac{(2)10^9 k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left(\frac{\pi}{2} - 0\right) = \frac{10^9 k}{2v^2 \log_\epsilon \frac{S}{r}} \text{ farads per centimeter of conductor} \qquad (10)$$

Substituting dimensions of test circuit and conversion factors in eq 10 for infinite neutral plane ($k = 1.0$)

$$C = \frac{(2.54)(12)(10^9)(1)}{(2)(9 \times 10^{20})(2.303) \log_{10} \frac{S}{r}}$$

$$= \frac{7.35 \times 10^{-12}}{\log_{10} \frac{S}{r}} \text{ farads per foot of line} \qquad (11)$$

For test plate 71.8 cm wide, 24 in. (60.95 cm) from conductor, $x_1 = 0$, and $x_2 = 35.9$ cm, from eq 9

$$C = \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{71.8}{121.9} - \tan^{-1} 0 \right]$$

$$= \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} (0.169\pi)$$

$$= \frac{(0.169)(10^9)k}{v^2 \log_\epsilon \frac{S}{r}} \text{ farads per centimeter} \qquad (12)$$

In air, from eq 12

$$C = \frac{(0.169)(10^9)(12)(2.54)}{9(10^{20})(2.303) \log_{10} \frac{S}{r}}$$

$$= \frac{2.49 \times 10^{-12}}{\log_{10} \frac{S}{r}} \text{ farads per foot of plate} \qquad (13)$$

For test plate 71.8 cm wide, 36 in. (91.4 cm) from conductor, $x_1 = 0$, and $x_2 = 35.9$ cm, from eq 9

$$C = \frac{(2)(10^9)k}{2\pi v^2 \log_\epsilon \frac{S}{r}} \left[\tan^{-1}\frac{71.8}{182.8} - \tan^{-1} 0 \right]$$

$$= \frac{(0.1192)\pi(10^9)k}{\pi v^2 \log_\epsilon \frac{S}{r}} \text{ farads per centimeter of plate} \qquad (14)$$

In air, from eq 14

$$C = \frac{(0.1192)(12)(2.54)(10^9)}{(9)(10^{20})(2.303) \log_{10} \frac{S}{r}}$$

$$= \frac{1.754 \times 10^{-12}}{\log_{10} \frac{S}{r}} \text{ farads per foot of plate} \qquad (15)$$

Bibliography

1. The Law of Corona and the Dielectric Strength of Air—II, F. W. Peek, Jr. A.I.E.E. Trans., v. 31, 1912, p. 1051–92.

2. An Oscillograph Study of Corona, Edward Bennett. A.I.E.E. Trans. v. 32, 1913, p. 1789–1809.

3. The Electric Strength of Air Under Continuous Potentials and as Influenced by Temperature, J. B. Whitehead and F. W. Lee. A.I.E.E. Trans., v. 40, 1921, p. 1201–37.

4. Radio Interference From Insulator Corona, F. O. McMillan. A.I.E.E. Trans., v. 51, 1932, p. 385–91.

5. A Method of Obtaining a Linear Time Axis for a Cathode Ray Oscillograph, A. L. Samuel. *Review of Scientific Instruments*, v. 2, 1931, p. 532–40.

6. Conductivity of Atmosphere at High Voltage, Harris J. Ryan. A.I.E.E. Trans., v. 23, 1904, p. 101–34.

7. Methods Used in Investigating Corona Loss by Means of the Cathode Ray Oscillograph, W. L. Lloyd, Jr., and E. C. Starr. A.I.E.E. Trans., v. 46, 1927, p. 997–1008.

8. The Electric Strength of Air—III, J. B. Whitehead. A.I.E.E. Trans., v. 31, 1912, p. 1093–1118.

9. Corona Loss Measurements on 220-Kv 60-Cycle Three-Phase Experimental Line, J. S. Carroll, Leland H. Brown, and D. P. Dinapoli. A.I.E.E. Trans., v. 50, 1931, p. 36–43.

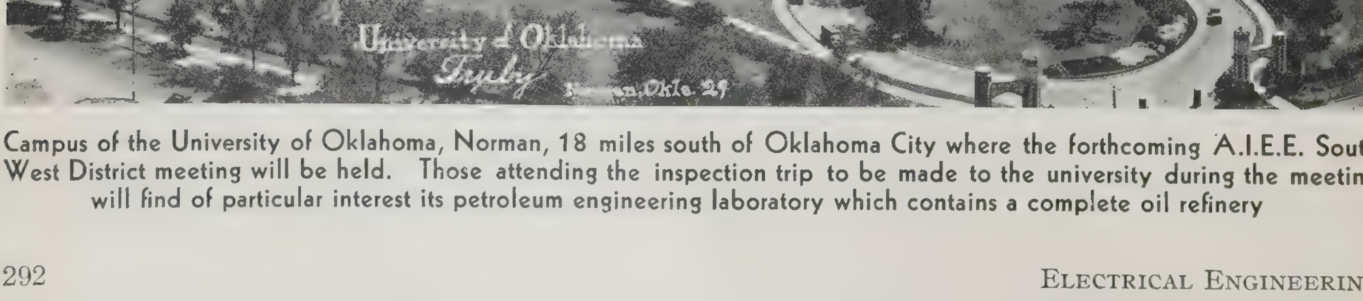
10. Corona Versus Conductor Surface, W. D. Weidlein. Elec. Engg., v. 50, Nov. 1931, p. 898–9.

11. The Theory of Ionization of Gases by Collision (a book), John S. Townsend. D. Van Nostrand Co.

12. The Space Charge That Surrounds a Conductor in Corona, J. S. Carroll and J. T. Lusinian. A.I.E.E. Trans., v. 47, 1928, p. 50–7.

13. Space Charge and Current in Alternating Corona, C. H. Willis. Jl. of the A.I.E.E., March 1927, p. 272–81.

14. The Law of Corona and the Dielectric Strength of Air—IV, F. W. Peek. A.I.E.E. Trans., v. 47, 1927, p. 1009–20.



Campus of the University of Oklahoma, Norman, 18 miles south of Oklahoma City where the forthcoming A.I.E.E. South West District meeting will be held. Those attending the inspection trip to be made to the university during the meeting will find of particular interest its petroleum engineering laboratory which contains a complete oil refinery

Methods of Electrical Prospecting

Electrical methods of prospecting are becoming increasingly important as the search for hidden deposits of ore extends deeper and deeper below the surface of the earth. Electrical prospecting is not limited to this use, however; it has found many valuable applications in engineering and in geology. The 4 general methods of electrical prospecting are described briefly in this paper.

By
DONALD G. FINK*

"electronics,"
New York, N. Y.

EVER SINCE man has known that mineral wealth lies hidden in the earth, he has been devising schemes for unearthing that wealth with the least possible effort. The search for a divining rod is, in fact, older than the equally dubious arts of alchemy. Only in comparatively recent years, however, have successful, and therefore accredited, schemes for divining the earth been developed. The success of these newer methods would not account for the high interest shown in them were it not for the real need that exists for some reliable method of subsurface exploration. This need is made only too clear by the fact that rocks that can be seen from the surface constitute only 1 per cent of the total area of mining districts. Since by now this easily available 1 per cent has been thoroughly exploited, the attention of prospectors has been turned to the remaining 99 per cent which lies hidden beneath the surface—a portion none the less valuable, but vastly harder to explore. In the search for these hidden deposits, electrical methods are beginning to play an important part, and the importance of electricity in this field may be expected to increase. It is the purpose of this paper to review briefly the more important methods of electrical prospecting and to emphasize their possibilities and limitations.

All Methods Fundamentally Similar

One general statement may be made at the outset. All methods of geophysical prospecting, which is the general name for prospecting by gravitational, seismic, and electrical methods, are carried out in the same fundamental way, that is, by measurement of the response of rocks and ore bodies to various types of physical fields, such as the field of gravity, electric and magnetic fields, and seismic shocks. The study of electrical prospecting is, therefore, the study of the appropriate electric fields, the appropriate methods of response measurement, and, finally, the interpretation of the response. A field fitted to the particular problem at hand should be used, so that the response will be not only of maximum intensity, but also of a unique character. If this be done, the reactions of the ore may be distinguished from those of the other geological elements, and, in addition, reliable indications as to its size, shape, and depth may be obtained.

The various types of electric fields used are 4 in number; these give rise to 4 different types of electrical prospecting. It is convenient to discuss them in 2 groups, the "natural field" methods and the "artificial field" methods. The natural fields are provided by the earth itself; the artificial fields are produced by the prospector.

Magnetic Surveying

Magnetic surveying, the method to be described first, makes use of a natural field, that of the earth's magnetism. It is well known that the magnetic field of the earth is greatly intensified in the presence of certain magnetic ores. Hence, this type of ore may be located simply by measuring the field intensity at various points over the area to be explored. A pocket magnetic dip needle, which is nothing more than a compass needle mounted on a horizontal shaft, is the simplest and commonest method of doing this; but refined magnetic balances have been developed which are much more sensitive. The usual field magnetometer, for example, will detect changes in the earth's magnetic field intensity of as small an order as 3 parts in 10,000.

Important iron ores, such as magnetite, and some nickel ores, may be detected in this way. Iron pyrites, however, better known as "fool's gold," are magnetically inert. Magnetically inert ores cannot be explored by this method, of course, but this fact is at once a disadvantage and an advantage. Magnetite, a strongly magnetic ore, is distributed so widely that it may be used as an index for the discovery of other types of deposit. Quarry rock has been discovered in New England by this method, simply because it contained $^1/_2$ per cent of magnetite. The magnetic method has had many such commercial successes.

Self-Potential Method

The second natural earth field that is used is less obvious than the magnetic one. This field is known as the "self-potential" field. It arises from the fact that many ores, particularly the sulphides, are chemically active. Differences in the degree of oxidation give rise to a difference of electric potential between various parts of the ore. A current flow

Full text of a paper recommended for publication by the A.I.E.E. committee on application to mining work. Manuscript submitted Dec. 14, 1933; released for publication July 10, 1934.

*Formerly Enrolled Student A.I.E.E., and formerly research assistant in the department of geology at the Mass. Inst. of Tech., Cambridge.

thus is established which creates a potential distribution throughout the ground. The intensity of this potential field on the surface may be measured by placing 2 electrodes, in the form of porous cups filled with copper sulphate, on the ground and measuring whatever potential appears between them with an ordinary potentiometer. The electrodes are moved

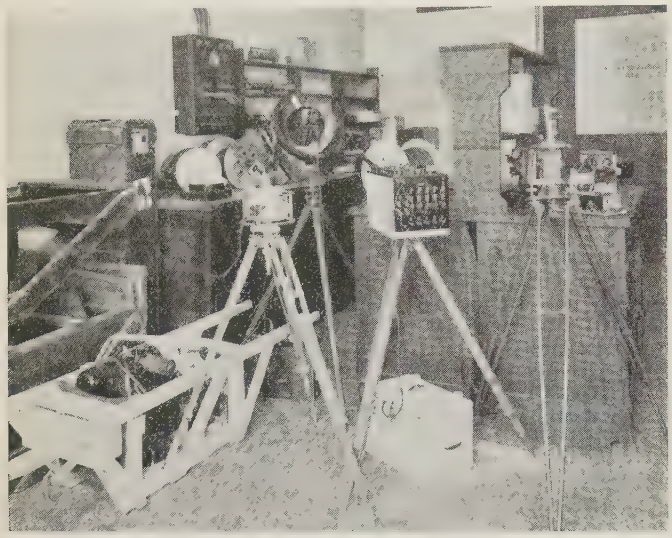


Fig. 1. A group of instruments used in geophysical prospecting by the department of geology at Massachusetts Institute of Technology

At the lower left is a portable gasoline-engine-driven alternator used in the inductive method of prospecting. On the tripods, from left to right: a Helmholtz balance for magnetic surveying; receiving coil and amplifier for inductive prospecting; complete apparatus for commutated direct current surveying; and a magnetic balance

from one location to another, and the process of measuring the potential difference between them is repeated at each location. By covering the terrain in this manner, a map of the existing surface potential may be made. The singularities or distortions in the map indicate the source of the current. The interpretation of the map is difficult, since it is complicated by numerous chemical reactions occurring in the ground independent of the ore body. This method is used extensively, however, because the field is localized about the ore, and because the method is cheap and rapid and may be carried out easily in conjunction with other methods.

These natural fields, the magnetic and the self-potential, have the advantage that they are provided free of charge; there is an attendant disadvantage in the fact that the excitation of the ore is not under the control of the prospector. The artificial fields offer a much more fertile field for the exercise of engineering ingenuity. By their use the prospector may choose the particular type of field, or combination of fields, best suited to his problem, and he may use it under control. Moreover, the use of artificial fields is suited particularly to exploration for deposits having high electrical conductivity, and it is a significant fact that many commercially valuable ores do possess this property. Hence the methods about to be described are of considerable commercial importance, but the results are often misleading and they must be used with skill and judgment.

Inductive Method

The first of the artificial field methods, the so-called inductive method, makes use of a sinusoidally varying magnetic field. The frequency of oscillations used depends upon the type of ore it is desired to locate, and, equally, upon the surrounding rocks. Usually a frequency of from 500 to 1,000 cycles per second is used. The field is produced by a large loop antenna, energized by a gasoline-engine-driven alternator of the correct frequency. One type of loop is triangular in shape, about 25 ft on a side, and set up in a vertical plane. Other systems use a horizontal loop of greater extent.

The theory of the measurement is this: The lines of force in the magnetic field at a distance from the loop lie, in general, in a plane perpendicular to the plane of the loop; but if an ore body interferes with this field, eddy currents are set up in the ore body, and these eddy currents in turn set up a secondary field. The original field and the secondary field combine in a resultant field the direction of which at the point in question is changed from the direction of the original field. The situation is closely analogous to that of armature reaction in d-c machines. By means of locating the changes in field direction caused by such reactions, the ore body may be located. It becomes necessary, then, to measure the direction of field intensity at many different points.

To measure the field direction, a receiving coil, to which an amplifier and a pair of headphones are attached, is mounted on a tripod in gimbals, so that the plane of the coil can assume any position relative to the ground plane. The plane of the receiving coil then is rotated about its vertical axis until the sound in the headphones is minimum; the plane of the coil then coincides with the horizontal component of the field intensity; knowing this direction, the direction of the resultant field may be determined by rotating the coil about its horizontal axis until the sound is minimum. By making a systematic series of such observations over the area, the magnetic field may be mapped, and the distortions caused by ore bodies discovered. However, it remains for a skillful interpreter to locate the ore bodies accurately.

Surface Potential Method

The method to be described last is called the surface potential method. In this method, an electric field is set up by sending a commutated direct current through the ground. To establish this field 2 power electrodes are driven into the ground above the suspected ore body, separated by as large a distance as is practicable, often several thousand feet or more. These power electrodes then are connected to a source of direct current, such as a battery

or a gasoline-engine-driven generator, but they are connected through a commutating mechanism. Usually ordinary ring commutators are used. As the commutator turns, a reversing voltage is applied to the electrodes, and as a result a reversing current flows through the ground, thereby creating a potential field the polarity of which reverses with each commutation.

Two pick-up electrodes, entirely independent of the power electrodes then are placed at any 2 locations in the area. These pick-up electrodes are connected to a second commutator, which turns on the same shaft as that of the power commutator. Thus, as the power circuit is commutated, the pick-up circuit is commutated in synchronism. The reversing potential that appears between the pick-up electrodes thereby is "rectified" back to d-c pulses, which can be measured on a potentiometer. The potentiometer is connected only during the steady state part of each pulse, so that the inductive effects during each build-up and build-down period will not affect the measurement. In other words the measurement is essentially a d-c one, and as such it is easier to carry out accurately than the a-c measurements of the inductive method.

The aim of the commutation is this: Contact potentials and potentials arising from chemical reactions are often of the same magnitude as the potentials to be measured. These stray potentials, therefore, must be eliminated. The commutation performs this task by averaging out to zero all potentials except those produced by the power circuit.

By choosing a sufficient number of points and by measuring the potential that appears between any 2 of them, a map of the surface potential may be made. Any distortions in this map indicate, through proper interpretation, the presence of conducting bodies.

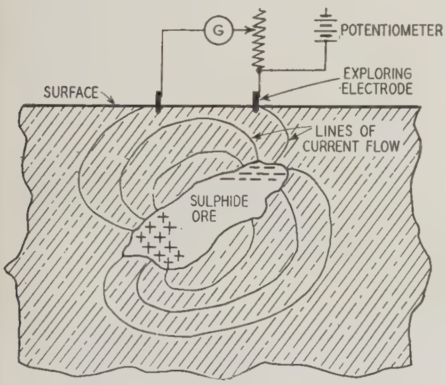


Fig. 2. An idealized view of the self-potential method

Current flow between parts of the sulphide ore sets up a potential gradient at the surface which can be measured with a potentiometer

Surprisingly accurate maps may be made by this method, but it remains for proper interpretation to locate correctly whatever conducting ore bodies may be present.

An Application to Geological Research

This description of the 4 most important methods of electrical prospecting must not lead one to believe that they are restricted to the vulgar purpose of revealing rich ore deposits. They have also many valuable applications in general engineering such as locating the depth to bed rock and faults in foundation problems, locating underground water supplies, and many others. In pure geology electrical prospecting is a tool of no mean significance. One such application to a problem in geological research with which the author had the pleasure of being associated

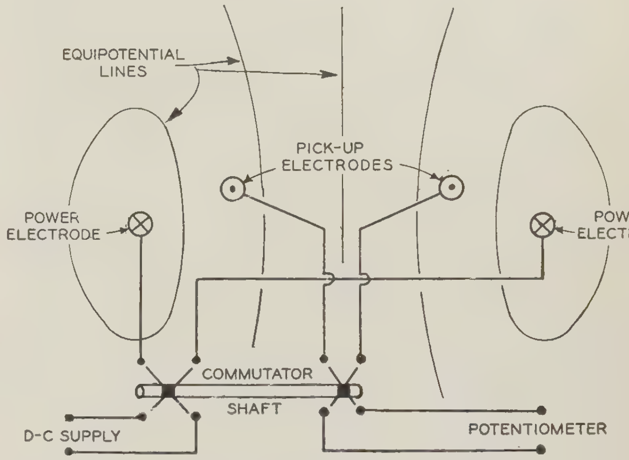


Fig. 3. The commutated d-c method, shown in plan view

The equipotential lines set up by the current flow are explored by the pick-up electrodes. Ore or other conducting material is indicated by distortions of the equipotential lines. Simultaneous commutation of power and pick-up circuits eliminates extraneous potentials

will be described; this work was carried out under the direction of Professor L. B. Slichter of the geology department of Massachusetts Institute of Technology. The purpose of this initial research was to develop experimental technique in the study of the electrical properties of the earth's crust at great depths. The method adopted was the commutated direct current method just described.

In this method it is clear that the greater the distance between the electrodes, the deeper into the earth will go the bulk of the current. Hence to find the conductivity of the earth at great depths, the electrodes must be separated by a great distance. In this project, the separation was about 30 miles. The electrodes used were power substation grounds located at Clinton and West Roxbury, Mass. The return circuit for the current was a 66-kv transmission line, used through the coöperation of the New England Power Association and the Edison Electric Illuminating Company. A maximum current of 25 amp was sent through this circuit (transmission line and ground return) and this current was commutated once every second. The engineering difficulties encountered in commutating this current in a circuit of more than $^1/_4$ h inductance, quickly enough so that the steady state period could exist for a large percentage of each reversal, were overcome by the use of a specially designed progressive suppressor circuit. The resulting commutation with this suppressor in

use was accompanied by only barely visible arcing.

Pick-up electrodes in the form of 3-ft iron rods were placed at more than 60 locations throughout the eastern half of the state, an area of some 2,500 square miles. By connecting these rods with telephone lines loaned by the New England Telephone Company, the potentials appearing between them were led to the central measuring station at Clinton. By using grounds in telephone central offices, the total number of potential measurements was increased to 92. The resulting map, now in process of construction, is the most comprehensive and perhaps the most ambitious of its kind ever constructed.

On the assumption that the conductivity of the earth varies only with depth, it is possible to deduce from such surface measurements the unknown conductivity function. The depth to which such interpretation may be carried depends upon the horizontal distances from the power electrodes over which potential measurements are available. Ordinarily, the depth is limited to about $^1/_5$ of the distance separating the power electrodes. In this case, therefore, if the conditions of symmetry had been realized, the distance was between 5 and 6 miles, a depth far exceeding the possibilities of attainment by direct drilling.

Interpretation of Maps Difficult

Little has been said about the specific methods of interpretation applied to the different types of maps that may be constructed by these methods, because the potential theory involved is difficult, and also because experience and judgment play so large a part in it. Often the problem is reproduced on a small scale in the laboratory, and an attempt made to reproduce the given map from different configurations of conductors.

In general, the problem of interpretation may be stated in this way: "Given a definite type of distortion in a geophysical prospecting map, is it possible to predict definitely the type, the size, the location, and the depth of ore body that caused that distortion?" Generally speaking it is not possible to do so; but with experience, and by using all the information mining engineers and geologists are able to supply, and by using all possible methods of geophysical prospecting, enough information may be amassed so that the resulting conclusions are not far from the geological truth.

It is, of course, a great deal to expect that any one type of exploration will indicate any more than one property of the deposit; and even though all the electrical and physical properties of the deposit could be determined, whether or not the ore were worth mining still would remain an open question. It is well to remember, therefore, that the results of electrical prospecting are not a law unto themselves but rather must be used as an aid, very often a very valuable aid, to the methods of prospecting that have been in existence since mining began. It is well to remember also that the urgency of finding a successful electrical divining rod has led to many abuses of the methods here described which in no way detract from their essential value.

Inductance of Steel Reënforced Aluminum Cable

Calculated values of inductance of steel reënforced aluminum cable, presented in this paper, show that previously published values of inductance obtained experimentally are in error by amounts ranging up to 5 per cent. Furthermore, all these errors are on the low side, that is, the unsafe side from the standpoint of the design engineer.

By
L. F. WOODRUFF
MEMBER A.I.E.E.
Mass. Inst. of Tech.
Cambridge

When theory and experiment fail to agree, usually the theory must be amended. Therefore the writer at first regarded with much suspicion his own calculated values of the inductance of aluminum cable, steel reënforced (A.C.S.R.) when he found rather important discrepancies between them and the corresponding experimental values that have formed the basis for extensive published tables.[1, 2] Careful and repeated checks of the theoretical work, however, revealed no errors. The method and difficulty of obtaining the experimental results that formed the basis for tables referred to will be examined.

Inductance values were based upon laboratory tests made at one-foot spacing; for other spacings the values were calculated from those at one-foot spacing by means of the fundamental inductance formula. Apparently, there has been no publication of the actual test data or a description of the method of test, but inquiry has revealed that the tests were made on short specimens, less than 100 feet long. The inductance measured was of the order of 10^{-5} henry, and a limit of error of 1 per cent therefore would require measurement within 10^{-7} henry of the true value. This presents some difficulties, and perhaps the results were as good as could be expected, especially since the correction for end effects still would remain to be made before the test results would be ready for use in applying to long lines. On such short specimens the end effects easily might amount to several per cent of the total. On the basis of these experimental difficulties, and the soundness of the theoretical attack, it can be stated positively that the experimental results are in error by amounts ranging up to 5 per cent in the determination of the inductance, which is the

A paper recommended for publication by the A.I.E.E. committee on power transmission and distribution. Manuscript submitted Oct. 9, 1933; released for publication Aug. 3, 1934.

1. For all numbered references see list at end of paper.

constant most effective in determining the power capacity and voltage regulation of a transmission line. Further, all these errors are on the low side, that is, the unsafe side from the standpoint of the design engineer.

It is shown in the Appendix that a *lower limit* for the value of inductance of A.C.S.R. may be calculated accurately, based upon the assumption of zero current in the steel reënforcement. Table I shows the comparison of the computed lower limit with the test results for one-foot spacing.

Table I—Comparison of Test and Calculated Values of Inductance of A.C.S.R.

Circular Mils (Aluminum)	No. of Strands: Aluminum	No. of Strands: Steel	Inductance in Mh per Mile of Each Conductor (1 Ft Spacing): Test[2]	Inductance in Mh per Mile of Each Conductor (1 Ft Spacing): Computed Lower Limit	Difference = Minimum Error in Test Value	Percentage Difference
1,590,000	54	7	0.906	0.9509	0.0449	4.7
1,510,500	54	7	0.912	0.9592	0.0472	4.9
1,431,000	54	7	0.920	0.9679	0.0479	4.9
1,351,500	54	7	0.928	0.9771	0.0491	5.0
1,272,000	54	7	0.938	0.9868	0.0488	4.9
1,192,500	54	7	0.948	0.9972	0.0492	4.9
1,113,000	54	7	0.957	1.008	0.051	5.1
1,033,500	54	7	0.968	1.020	0.052	5.1
954,000	54	7	0.981	1.033	0.052	5.0
900,000	54	7	0.990	1.043	0.053	5.1
874,500	54	7	0.994	1.047	0.053	5.1
795,000	54	7	1.01	1.062	0.052	4.9
715,500	54	7	1.03	1.079	0.049	4.5
666,600	54	7	1.04	1.091	0.051	4.7
636,000	54	7	1.05	1.098	0.048	4.4
605,000	54	7	1.05	1.106	0.056	5.3
556,500	30	7	1.05	1.100	0.050	4.5
500,000	30	7	1.07	1.117	0.047	4.2
477,000	30	7	1.08	1.124	0.044	3.9
397,500	30	7	1.11	1.154	0.044	3.8
336,400	30	7	1.14	1.181	0.041	3.5
300,000	30	7	1.16	1.199	0.039	3.3

Percentages tabulated in the last column of table I represent a *lower limit* to the percentage errors in the previously published tables, and not the actual errors. An approximation will be made to allow for the effect of the current in the steel strands. This effect is small. Table II presents values of reactance at a frequency of 60 cycles per second for various spacings, with allowance made for the effect of the steel reënforcement. It is believed that this table is accurate to within ± 0.5 per cent.

Conclusions

Errors up to 5 per cent have been pointed out in existing A.C.S.R. tables. A more accurate table is presented. It is recommended, however, that precise tests be made on one specimen of each stranding, that is, one cable of 54 + 7 strands, one of 30 + 7 strands, etc. Rational methods, pointed out in this paper, may be used to extend the results to other sizes having the same stranding. End effects may be handled in several ways—for example, by testing 2 different lengths of loop having identical end arrangements, and taking the difference of their inductances. The loops should be at least 200 or 300 feet long in order to provide accurate results.

While the theory suffices to show indisputably that large errors exist in the present tables, nevertheless certain assumptions have had to be made in the theoretical analysis. All these assumptions have been considered carefully, and their effects calculated or at least estimated. Table II is an improvement over the previously published tables, but the matter cannot be considered as settled satisfactorily until agreement between experimental and theoretical results has been reached.

Appendix

The inductance of A.C.S.R. conductors is affected by the following considerations:

1. Stranding of aluminum.
2. Spiraling of aluminum strands.
3. Skin effect.
4. Proximity effect.
5. Effect of steel core.

These effects will be considered in the order listed.

Stranding of Aluminum

This effect may be taken into account precisely by computing the geometric mean distance of the aluminum cross section to itself. (This sometimes is called geometric mean radius. However, it is not in any sense a radius, so this term is somewhat deceptive.) There are 4 well established theorems that will be used in the computation, namely:

a. Self geometric mean distance of a circular area is $r\epsilon^{-1/4}$ where r = radius and $\epsilon = 2.718\cdots$.

b. Geometric mean distance between 2 circular areas external to each other is equal to the distance between their centers.

c. Geometric mean distance from a circular line to any point, line, or area wholly enclosed by the circular line is equal to its radius.

d. If a circular line of radius r has on it n equally spaced points, the geometric mean distance among them[3] is $r\sqrt[n-1]{n}$.

Self Geometric Mean Distance of 54 Aluminum Strands. All strands are the same size (see figure 1) and are arranged in circular layers of 6, 12, 18, and 24 about the central strand. The 3 outer layers are aluminum. If the radius of a single strand be designated by ρ, the radii of the circles through the centers of successive layers will be 2ρ, 4ρ, 6ρ, and 8ρ. The self geometric mean distance of the entire aluminum area to itself, which will be called D_s, is

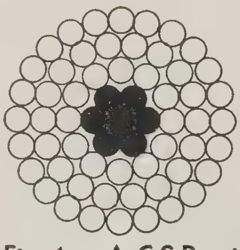


Fig. 1. A.C.S.R. with 54 aluminum and 7 steel strands

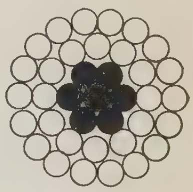


Fig. 2. A.C.S.R. with 30 aluminum and 7 steel strands

$$D_s = \sqrt[54^2]{(8\rho\sqrt[23]{24})^{23\times24}(6\rho\sqrt[17]{18})^{17\times18}(4\rho\sqrt[11]{12})^{11\times12}(8\rho)^{2\times24\times30}(6\rho)^{2\times18\times12}(\rho\epsilon^{-1/4})^{54}}$$

$$= \rho\sqrt[2916]{6^{810}\,4^{3141}\,\epsilon^{-54/4}} = 7.28883\,\rho = 0.495942\sqrt{A}$$

where A is the total area of aluminum expressed in circular measure, equal to $54(2\rho)^2$. In the large radical above, the first parenthesis is the geometric mean distance between strands in the outside layer;

Table II—Inductive Reactance of A.C.S.R. in Ohms per Mile at 60 Cycles per Second for One Conductor of a Single Phase or Equilateral 3-Phase Transmission Line

Circular Mils (Aluminum)	No. of Strands Alum.	No. of Strands Steel	Interaxial Spacing in Feet 1	2	3	4	6	8	10	12	14	16	18	20	24	28	32	36	40
1,590,000	54	7	0.360	0.444	0.493	0.528	0.577	0.612	0.639	0.661	0.680	0.696	0.710	0.723	0.745	0.764	0.780	0.794	0.807
1,510,500	54	7	0.363	0.447	0.496	0.531	0.580	0.615	0.642	0.664	0.683	0.699	0.713	0.726	0.748	0.767	0.783	0.798	0.810
1,431,000	54	7	0.366	0.450	0.499	0.534	0.583	0.618	0.645	0.668	0.686	0.702	0.717	0.730	0.752	0.770	0.787	0.801	0.814
1,351,500	54	7	0.369	0.454	0.503	0.538	0.587	0.622	0.649	0.671	0.690	0.706	0.720	0.733	0.755	0.774	0.790	0.804	0.817
1,272,000	54	7	0.373	0.457	0.506	0.541	0.591	0.625	0.653	0.675	0.693	0.710	0.724	0.737	0.759	0.777	0.794	0.808	0.821
1,192,500	54	7	0.377	0.461	0.510	0.545	0.594	0.629	0.656	0.679	0.697	0.713	0.728	0.741	0.763	0.781	0.798	0.812	0.825
1,113,000	54	7	0.381	0.465	0.515	0.549	0.599	0.634	0.661	0.683	0.701	0.718	0.732	0.745	0.767	0.786	0.802	0.816	0.829
1,033,500	54	7	0.386	0.470	0.519	0.554	0.603	0.638	0.665	0.687	0.706	0.722	0.736	0.749	0.771	0.790	0.806	0.821	0.833
954,000	54	7	0.391	0.475	0.524	0.559	0.608	0.643	0.670	0.692	0.711	0.727	0.741	0.754	0.776	0.795	0.811	0.825	0.838
900,000	54	7	0.394	0.478	0.527	0.562	0.612	0.646	0.674	0.696	0.714	0.731	0.745	0.758	0.780	0.798	0.815	0.829	0.842
874,500	54	7	0.396	0.480	0.529	0.564	0.613	0.648	0.675	0.697	0.716	0.732	0.747	0.759	0.781	0.800	0.816	0.831	0.843
795,000	54	7	0.402	0.486	0.535	0.570	0.619	0.654	0.681	0.703	0.722	0.738	0.752	0.765	0.787	0.806	0.822	0.836	0.849
715,500	54	7	0.408	0.492	0.541	0.576	0.625	0.660	0.687	0.710	0.728	0.744	0.759	0.772	0.794	0.812	0.829	0.843	0.856
666,600	54	7	0.412	0.496	0.546	0.581	0.630	0.665	0.692	0.714	0.733	0.749	0.763	0.776	0.798	0.817	0.833	0.847	0.860
636,000	54	7	0.415	0.499	0.548	0.583	0.633	0.668	0.695	0.717	0.735	0.752	0.766	0.779	0.801	0.820	0.836	0.850	0.863
605,000	54	7	0.418	0.502	0.552	0.586	0.636	0.671	0.698	0.720	0.738	0.755	0.769	0.782	0.804	0.823	0.839	0.853	0.866
556,500	30	7	0.416	0.501	0.550	0.585	0.634	0.669	0.696	0.718	0.737	0.753	0.767	0.780	0.802	0.821	0.837	0.851	0.864
500,000	30	7	0.423	0.507	0.556	0.591	0.640	0.675	0.702	0.724	0.743	0.759	0.774	0.786	0.809	0.827	0.843	0.858	0.871
477,000	30	7	0.426	0.510	0.559	0.594	0.643	0.678	0.705	0.727	0.746	0.762	0.777	0.789	0.811	0.830	0.846	0.861	0.873
397,500	30	7	0.437	0.521	0.570	0.605	0.654	0.689	0.716	0.738	0.757	0.773	0.788	0.800	0.822	0.841	0.857	0.872	0.884
336,400	30	7	0.447	0.531	0.580	0.615	0.664	0.699	0.726	0.749	0.767	0.783	0.798	0.811	0.833	0.851	0.868	0.882	0.895
300,000	30	7	0.454	0.538	0.587	0.622	0.671	0.706	0.733	0.755	0.774	0.790	0.805	0.817	0.840	0.858	0.874	0.889	0.902

the second is that between strands in the second outer layer; the third, between strands in the third or inner layer of aluminum; the fourth, from the outer layer to all aluminum strands inside it; the fifth, between the strands of the second and third layers; and the last parenthesis is the geometric mean distance of each strand to itself.

Self Geometric Mean Distance of 30 Aluminum Strands. Similarly, for the 30 aluminum strands of figure 2,

$$D_s = \sqrt[30\times 30]{(6\rho\sqrt[17]{18})^{17\times 18}(4\rho\sqrt[11]{12})^{11\times 12}(6\rho)^{2\times 18\times 12}(\rho\epsilon^{-1/4})^{30}}$$

$$= \rho\sqrt[900]{6^{786}\,4^{129}\,\epsilon^{-30/4}} = 5.78446\,\rho = 0.528045\sqrt{A}$$

where A for this design is $30\,(2\rho)^2$, the total area of aluminum in the cross section.

The inductance calculated on the basis of the aluminum strands only may now readily be obtained, assuming uniform current density over the aluminum. For the 556,500 circular mil 30 + 7 strand A.C.S.R. at 12 inch interaxial spacing, it is

$$0.74113\log_{10}\frac{D_M}{D_s} = 0.74113\log_{10}\frac{12}{0.5280\sqrt{0.5565}} = 1.100 \text{ millihenry}$$

per mile of conductor.

Spiraling of Aluminum Strands

The spiraled strands of aluminum comprise long concentric solenoids with some compensation from the alternate directions of twist in the successive layers. The magnitude of the inductance contributed by spiraling in the 556,500 circular mil 30 + 7 strand A.C.S.R. will be discussed. The outer layer consists of 18 strands of aluminum with a lay of one revolution in about 12 inches. The second layer consists of 12 strands of aluminum, and has a reverse lay of one revolution in about 8 inches. The axial magnetomotive forces of the 2 layers, therefore, will very nearly cancel inside the second layer. The main solenoid flux, therefore, will be confined between the outer and second layers, and will have a magnetomotive force of about 18/30 ampere turn per foot for each ampere of total current since the steel carries very little current, as will be shown later. The annular area of cross section of the flux path is 0.292 square inch. The return path will be outside the cable, so each line of solenoidal flux will link only the outer layer, carrying 18/30 of the current. The inductance contributed by this spiraling, therefore, will be $(5280\times\frac{18}{30}\times\frac{18}{30}\times 4\pi\times 6.45\times 0.292)\div(30.5\times 10^6) =$ 0.0115 millihenry per mile of each conductor.

The effect is of the order of $^1/_{10}$ of one per cent. It may be noticed that the effect of spiraling always will be to *increase* the inductance, and so the effect is in the wrong direction to account for any part of the large discrepancy of several per cent.

Skin Effect

Skin effect in a solid round wire of radius r reduces that portion of the total inductance due to flux inside the wire by a factor equal to[4] the difference between unity and the real part of $\frac{4}{nr}\,\frac{J_0(nr)}{J_1(nr)}$ where $n = \sqrt{-j\,4\pi\mu\omega\gamma}$ and J_0 and J_1 indicate Bessel functions of the first kind and of zero and first order, respectively, μ is the permeability, ω is the angular velocity of the current, and γ the conductivity in absolute centimeter-gram-second units. The total effect is small at power frequencies, and it has been shown by Kennelly, Laws, and Pierce[5] that the combination of air and metal in a large stranded conductor has very nearly the same skin effect as the equivalent solid conductor. On this basis, it is found that the correction to be applied because of skin effect amounts to 0.0007 millihenry per mile for the 556,500 circular mil cable at a frequency of 60 cycles per second.

A slightly more accurate figure for the skin effect can be obtained by considering the aluminum strands as a hollow tube having inner and outer radii q and r, respectively. Then the internal inductance is[6] the real part of

$$\frac{2}{nr}\,\frac{J_0(nr) - \dfrac{J_1(nq)}{G_1(nq)}\,G_0(nr)}{J_1(nr) - \dfrac{J_1(nq)}{G_1(nq)}\,G_1(nr)} \text{ abhenries per centimeter}$$

and the correction to be applied becomes 0.0006 millihenry per mile. The correction is negligible, about $^1/_{20}$ of one per cent. The effect is to reduce the inductance, so that there is a partial cancellation between this effect and the small increase in inductance resulting from spiraling.

Proximity Effect

The approximate importance of proximity effect at the one foot spacing used in the tests may be computed from the round wire formula. The effect[7] is to *reduce* the inductance by an amount equal to $2\sum_{1}^{\infty} m\left(\frac{r}{D}\right)^{2m}\phi_{m,o}$ abhenries per centimeter for one conductor. (See reference 7 for definition of $\phi_{m,o}$.)

For the particular size and spacing under consideration, the correction to be applied is a reduction of only 0.000019 millihenry per mile. It is absolutely negligible. If this correction were not so very small it might be desirable to compute the proximity effect on the equivalent aluminum tubes.[8] Proximity effect in a spiraled cable is less than in a solid equivalent conductor because the circular dissymmetry of the current distribution requires leakage across the boundaries of the individual strands as the current progresses in an axial direction; hence the true proximity effect is even smaller than the very small figure just given.

There are 2 or 3 other minor corrections that have a slight effect on the inductance. If the over-all diameter of the cable be increased because of either oxidation or loosening of the strands, a slight decrease in inductance would result. For each per cent increase in diameter the decrease in inductance would be only about $^1/_4$ of one per cent at spacings of about one foot, and less at larger spacings. It seems very unlikely that this could be of any importance in an actual line, under tension, although perhaps this effect was appreciable in the experimental set-up.

If the lay of the strands in all layers, expressed in turns per unit length, were the same, then the strands in the inner layers would be shorter and would tend to carry somewhat more current than the outer ones because of their lower resistance. This would offset somewhat the skin effect, which tends to cause a crowding of current toward the outside. It seems to be the manufacturing practice, however, to give more twist to the inner strands, about in proportion to the diameter of the layer, so that the aluminum strands in different layers actually do have almost identical lengths and resistances.

Total Inductance of Aluminum Strands

Before considering the effect on the inductance of the current and flux in the steel strands, which may involve more uncertainty than the other considerations because of the comparatively high and varying permeability, it is instructive to review all the other effects. It has been shown that the computation involving geometric mean distance gives very nearly the exact inductance for the aluminum. There is a slight positive correction to be added, since the effect of spiraling appears to add about twice as much inductance as the reduction resulting from skin effect and proximity effect combined. At large spacings the proximity effect is even smaller. The net correction is less than $^1/_{10}$ of one per cent. For the very large sizes, the increase in inductance resulting from spiraling and the decrease resulting from skin effect both become somewhat greater, but their difference remains very small.

Current and flux in the steel core necessarily *increase* the inductance over its value for the hollow aluminum portion alone for A.C.S.R. at usual power frequencies. To prove this, consider the effect of transferring part of the current from one layer of aluminum strands to the more central steel. This change would leave unaffected the magnetic field outside the aluminum layer, but would *increase* the strength of the field within it and hence cause more linkages and more inductance.

Therefore, the accurately computed inductance for the aluminum alone constitutes a lower limit to the possible value of inductance. The fact that the existing tables present values considerably lower than this lowest possible value is conclusive evidence that important errors exist in those tables.

Although the error can be shown to exist by neglecting all current in the steel, the lower limit computed in this way is not a satisfactory value to use as the basis for a standard table. A very good approximation of the true effect of the steel core can be made.

Effect of Steel Core

The boundary condition controlling the determination of the relative currents in the aluminum and the steel portions is that at the surface of contact of the 2 metals the current densities are in direct proportion to the respective conductivities. The particular case of the 536,500 circular mil A.C.S.R. at a frequency of 60 cycles per second will be considered. It has been shown already that the skin effect in the aluminum is very small. The skin effect in the steel is unaffected by the tubular aluminum sheath, and so would be the same as for a 7 strand steel cable of the same size. Test data are available[9] on such cables. At 60 cycles per second the skin effect resistance ratio is 1.007 at 10 amperes and 1.013 at 20 amperes for Siemens Martin steel. This indicates that the current density throughout the steel is approximately uniform, since otherwise the resistance ratio would be considerably more than one. The current distribution in the steel is therefore but little affected by the alternating character of the current. The current will divide almost exactly inversely as the d-c resistance of the 2 paths. The resistivity of the steel is about 110 ohms per mil-foot at 20 degrees centigrade, and of aluminum about 17.0 ohms per mil-foot. The aluminum will carry $\frac{30}{7} \times \frac{110}{17.0} = 27.7$ times as much current as the steel. The steel wire will carry 1/28.7 or 3.48 per cent in the cable under consideration. The effect of this core current on the inductance now will be computed and applied as a correction to the calculations already made, in which the effect of core current was neglected. First it is noted that the removal of 3.48 per cent of the current from the aluminum and its flow in the steel has no effect whatever upon the magnetic flux external to the entire cable. It will increase the flux density in the aluminum region by an amount that varies from zero at the outside to a maximum at the inside of the aluminum, where before the flux density was zero. The flux density in the steel is increased also, the value on the basis of assumed zero core current being zero throughout. If now the aluminum be considered as a tube of inside diameter 0.4086 inch and outside diameter 0.9534 inch, the increase in flux linkages per centimeter length resulting from the increased flux in the aluminum is equal to

$$\int_{0.2043}^{0.4767} \frac{4\pi I}{2\pi x}\left(0.0348 + 0.9652\ \frac{x^2 - 0.2043^2}{0.4767^2 - 0.2043^2}\right)^2 dx - \int_{0.2043}^{0.4767} \frac{4\pi I}{2\pi x}\left(\frac{x^2 - 0.2043^2}{0.4767^2 - 0.2043^2}\right)^2 dx = 0.378\ I - 0.358\ I = 0.020\ I \text{ linkage per centimeter}$$

where I is expressed in abamperes. Applying the proper conversion factors this is found to represent an increase in inductance per mile of one conductor amounting to 0.00322 millihenry.

In addition to this there is another increase in inductance resulting from the linkages between the core current and core flux. Experimental results[9] on 7 strand steel cables of the size of the core indicate an internal inductance that varies slightly with the current, but an average value of 1.50 millihenries may be used. In order to make use of this datum for A.C.S.R., it must be multiplied by the square of the fraction of current carried by the steel, or 0.0348. The contribution to the inductance is therefore $0.0348^2 \times 1.50 = 0.00182$ millihenry per mile. The total increase resulting from the presence of the steel in the center instead of a nonconductor is $0.00322 + 0.00182 = 0.00504$ millihenry per mile. The same increase would apply to other A.C.S.R. cables of different size provided they are geometrically similar, i. e., composed of 30 + 7 strands of aluminum and steel, respectively. For the 54 + 7 strand A.C.S.R. the corresponding increase works out to be $0.0017 + 0.0006 = 0.0023$ millihenry per mile.

These corrections, added to the computed lower limits of inductance listed in table I, form the basis for the reactance figures presented in table II.

For reënforcement of standard low-carbon steel strand the permeability is higher, and the skin effect resistance ratios are 1.13 and 1.35 at 10 and 20 amperes, respectively. The measured internal inductance is about 4.5 millihenries per mile, an average value over the range of probable current density. The steel core therefore will carry about 25 per cent less current than before. The increase in inductance resulting from additional linkages in the aluminum region will be decreased to 0.0024, and in the steel there will be a total increase of $0.026^2 \times 4.50 = 0.0030$ millihenry per mile. The total change resulting from the steel is 0.0054 compared with 0.0050 for the less permeable steel—a negligible difference.

The question might be raised as to how computations of inductance based upon measurements made on steel cables can pretend to greater accuracy than values obtained by direct measurement on A.C.S.R. cables. The answer of course is that experimental error introduced in the measurements on the steel cable affect only about $^1/_2$ of one per cent of the entire A.C.S.R. inductance, the other 99.5% being computed by well established fundamental methods.

References

1. A.C.S.R. Electrical Characteristics (pamphlet), Aluminum Company of America.

2. Electrical Characteristics of Transmission Circuits, Westinghouse Elec. and Mfg. Co., third edition, 1926.

3. C. E. Guye, *Comptes Rendus*, v. 118, 1894, p. 1329.

4. Mathematical and Physical Papers, Kelvin, v. 3, p. 491.

5. Experimental Researches on Skin Effect in Conductors, Kennelly, Laws, and Pierce. A.I.E.E. Trans., 1915, v. 34, p 1953.

6. Electrical Papers, Heaviside, v. 2, p. 67, *et seq.*

7. Elek. Wellen an zwei paralellen Drahten, Mie. *Annalen der Physik* 1900, p. 201.

8. Wave Propagation Over Parallel Tubular Conductors, Mead. *Bell System Tech. Jl.*, v. 4, 1925, p. 327.

9. Report to Indiana Steel and Wire Co., Frank F. Fowle (pamphlet), 1921.

Saturated Synchronous Reactance

It is well known that the effects of magnetic saturation are important in modifying the operating characteristics of synchronous machines. In this paper is shown a method of accurately taking into account these effects on the balanced steady-state operation of a cylindrical rotor synchronous machine by using a saturated value of the synchronous reactance. The expression for this reactance is derived directly from fundamental principles, and its use in calculating machine characteristics accurately is illustrated on a typical steady state stability problem.

By
CHARLES KINGSLEY, JR.
ASSOCIATE A.I.E.E.
Mass. Inst. of Tech., Cambridge

As is well known, a cylindrical rotor synchronous machine operating without magnetic saturation under balanced polyphase load conditions can be represented by its synchronous impedance in series with its excitation voltage. However, it has long been realized that the effects of saturation should be correctly taken into account. Various empirical schemes[1,2] for adjusting the synchronous reactance have been proposed but, as shown in table I of this paper, these methods may give results which are considerably in error.

In a paper by Crary, March, and Shildneck[3] it is shown that with certain restrictions a saturated synchronous machine can be replaced by an "equivalent" unsaturated machine. However, in the cylindrical rotor case, this "equivalent" machine does not have the same load angle as the actual machine which it replaces, and hence the synchronizing power of the "equivalent" machine will not in general be the correct value for the actual saturated machine.[4] This may introduce considerable error, as shown in table II.

In a paper by H. V. Putman a simple expression is derived for the saturated synchronous reactance. This expression is derived directly from basically sound fundamental principles which take into account correctly the most important factors affecting saturation. The correct use of Putman's expression should therefore give accurate results. The difficulty in using Putman's expression arises from the fact that the saturated synchronous reactance is a variable. For example, in calculating the steady-state power-angle characteristics of a synchronous machine, the saturation has a different value for each point on the curve. Hence, a different value of the saturated synchronous reactance should be used in calculating each point, and in any calculations involving differentiation—for example, in calculating the steady state synchronizing power—the saturated synchronous reactance should be treated as a variable. In Putman's paper (equations 24 and 25) this fact is neglected, the saturated synchronous reactances being treated as constants in the differentiation. This may introduce considerable error, as shown in table II of this paper.

The methods of both Putman and Crary, March, and Shildneck require a knowledge of the air gap voltage of the machine in order to calculate its reactance. Many cases may arise in which the data are so stated that it is difficult to calculate the air gap voltage. For example, let the field current, terminal voltage, and power output of a saturated synchronous machine be given. It is necessary to resort to successive approximations in order to calculate the air gap voltage. Hence, the methods of Putman and Crary, March, and Shildneck are, practically speaking, restricted to cases where the terminal operating conditions are explicitly known.

This paper presents a treatment of the cylindrical rotor synchronous machine based upon Putman's expression for the saturated synchronous reactance. It is shown that by means of an auxiliary curve, the appropriate value of the saturated synchronous reactance can be determined in calculating each point on the power-angle characteristics of a typical simple system, and that the effects of saturation on the maximum power of such a system can be readily and accurately taken into account. The paper also shows a comparison of results obtained by tests with those obtained by various methods of calculation.

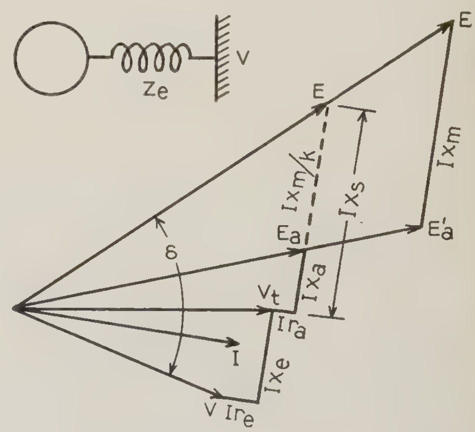


Fig. 1. Cylindrical rotor synchronous generator connected to an infinite bus

Assumptions

The assumptions are those which are commonly made in analyzing the steady-state performance of a

Full text of a paper recommended for publication by the A.I.E.E. committee on electrical machinery. Manuscript submitted Sept. 28, 1934; released for publication Feb. 1, 1935.

1. For all numbered references see list at end of paper.

cylindrical rotor synchronous machine.[6] Of these, the most important are:

1. The air gap is uniform. From this assumption, the direct-axis synchronous reactance X_d is equal to the quadrature-axis synchronous reactance X_q.

2. The saturation curve of the machine under load conditions is assumed to be the same as the open-circuit characteristic. According to this assumption the field leakage flux is assumed to have the same effect under load conditions as it has at no-load.

(In reference 3, at the end of the paper, the effects on the saturation of the change in field leakage flux under load conditions are approximately accounted for by using, instead of the open-circuit saturation curve, a family of load saturation curves calculated with the appropriate values of field leakage under load conditions. If deemed advisable, this refinement may be introduced. It is omitted in this paper in order to simplify the presentation of more essential facts.)

Saturated Synchronous Machine

Consider a saturated cylindrical-rotor synchronous machine operating under balanced steady-state conditions, connected through an impedance Z_e of resistance r_e and reactance x_e to an infinite bus of voltage V, as shown in figure 1. On the basis of the foregoing assumptions, the well-known vector diagram shown by the solid lines of figure 1 can be drawn,[3,6] in which

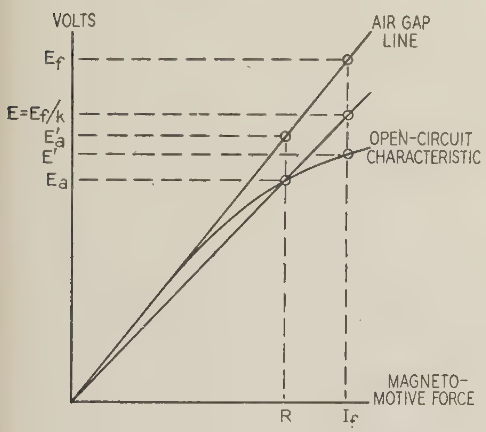


Fig. 2. Open-circuit characteristic

I = armature current
V_t = terminal voltage of the machine
r_a = armature effective resistance
x_a = armature leakage reactance
E_a = voltage generated by the resultant air gap flux
E_a' = voltage which would be generated by the resultant magnetomotive force R if the magnetic circuit were not saturated
E_f = voltage which would be generated by the field excitation I_f if the magnetic circuit were not saturated
X_d = unsaturated value of the synchronous reactance
$x_m = X_d - x_a$ = reactance equivalent to the armature reaction when there is no saturation

Any consistent system of units may be used. The voltages E_f and E_a' are shown in figure 2.

Let

$$k = E_a'/E_a \tag{1}$$

Then k is a measure of the saturation of the machine. (Except for the manner in which field leakage is treated, k as defined above is the same as the saturation factor k of reference 3 at the end of the paper.) Figure 4 shows a typical curve of k as a function of E_a.

By applying equation 1 to figure 1, it can be seen that the saturated value of the synchronous reactance is

$$x_s = x_a + x_m/k \tag{2}$$

and that the saturated value of the excitation voltage is

$$E = E_f/k \tag{3}$$

These results agree with those obtained by Putman.[5] Since k is a function of E_a, both x_s and E are functions of E_a. Figure 4 shows a typical curve of x_s as a function of E_a.

Equations 2 and 3 are derived directly from the fundamental vector diagram of figure 1, and hence take into account correctly the most important effects of saturation. This is an important improvement over any method of empirically adjusting the synchronous reactance.[1,2]

It can readily be seen that the voltage E in figure 2 is equal to the voltage E given by equation 3. (In figure 2, $E_f/E = E_a'/E_a = k$, or $E = E_f/k$). It should be noted that the excitation voltage E is not equal to the voltage E' read from the open-circuit saturation curve, figure 2. The voltage E' would appear at the machine terminals at no-load if the field current were maintained constant. Hence E' is frequently used as the excitation voltage. However, the removal of the load would change the saturation of the machine. The voltage E would appear at the machine terminals if the load were removed and the field current *and saturation* maintained the same as under load conditions. Hence equation 3 determines the excitation voltage at the correct saturation of the machine under load conditions.

Power-Angle Characteristics

Consider the system shown in figure 1. As is well known, the air gap power of the machine P_a is given by

$$P_a = \frac{EV}{Z}\sin(\delta - \alpha) + \frac{E^2 r}{Z^2} \tag{4}$$

and the power P_b delivered to the infinite bus is given by

$$P_b = \frac{EV}{Z}\sin(\delta + \alpha) - \frac{V^2 r}{Z^2} \tag{5}$$

where

r = total series resistance = $r_e + r_a$
x = total series reactance, saturated value = $x_e + x_s$
Z = total impedance = $\sqrt{r^2 + x^2}$
α = $\tan^{-1}(r/x)$
δ = load angle of the machine with respect to the infinite bus, i. e., the angle between the vector voltages E and V, positive when E leads V.

Positive values of P_a and P_b correspond to generator action of the machine. Equations 4 and 5 apply equally well when the machine is operating as a synchronous motor with negative values of δ, P_a, and P_b. Equations 4 and 5 are the well-known relations which are useful in steady state stability studies, written in a form which the author has found convenient.

As is well known, saturation affects the power-

angle characteristics, since it affects x_s and E. The following is an accurate method of calculating these curves, based upon equations 2 and 3 as expressions for x_s and E, which correctly take into account the most important effects of saturation.

Since $E = E_f/k$, equation 3, and is thus dependent upon saturation, it is more convenient to express equations 4 and 5 as follows:

$$P_a = \frac{E_f V}{kZ} \sin(\delta - \alpha) + \frac{E_f^2 r}{(kZ)^2} \tag{6}$$

$$P_b = \frac{E_f V}{kZ} \sin(\delta + \alpha) - \frac{V^2 r}{Z^2} \tag{7}$$

In equations 6 and 7, (kZ), α, and Z^2 are variables dependent upon the saturation. Even if the machine excitation and the bus voltage are constant, the saturation will vary with changes in the load angle δ. Therefore (kZ), α, and Z^2 are variables dependent upon δ. Hence, in order to determine the values of these quantities to use in equations 6 and 7, it is necessary to express the air gap voltage E_a (which determines the saturation) as a function of δ. The following equation is derived in appendix A:

$$(kZE_a)^2 = (E_f Z_c)^2 + (Vx_m)^2 + 2E_f V Z_c x_m \cos(\delta - \alpha_c) \tag{8}$$

where

$$Z_c = \sqrt{(r_e + r_a)^2 + (x_e + x_a)^2}$$
$$\alpha_c = \tan^{-1}[(r_e + r_a)/(x_e + x_a)]$$

On the left-hand side of equation 8, both k and Z are functions of E_a, as are the variables (kZ), α, and Z^2 which appear in equations 6 and 7. By assuming various values of E_a, these variables and the quantity $(kZE_a)^2$ which constitutes the left-hand side of equation 8 can be calculated and curves drawn showing (kZ), α, and Z^2 as functions of $(kZE_a)^2$. These auxiliary curves are shown in figure 5 for the case illustrated in example 1 (see below).

Having plotted these auxiliary curves for the system under consideration, the power-angle characteristics can be calculated for any given excitation of the machine and any given voltage of the infinite bus, as outlined in the following:

Assume a value of δ for which the corresponding values of P_a and P_b are to be calculated. From equation 8 calculate the corresponding value of $(kZE_a)^2$. From the auxiliary curves of (kZ), α, and Z^2 as functions of $(kZE_a)^2$, read the corresponding values of these quantities. Substituting these values the given values of E_f and V, and the assumed value of δ in equations 6 and 7, the corresponding values of P_a and P_b now can be readily calculated. By repeating this procedure for other assumed values of δ, the power-angle characteristics can be calculated, accurately taking into account the effects of saturation.

Numerical Example 1

Consider the cylindrical rotor synchronous machine whose open-circuit and short-circuit characteristics are given in figure 3. The armature resistance is $r_a = 0.022$ and the armature leakage reactance is $x_a = 0.105$, both expressed in "per unit" on the machine rating as a base. From the open-circuit characteristic, the saturation factor k can be calculated, equation 1, and plotted as a function of the air gap voltage E_a, as shown in figure 4. From the short-circuit characteristic and the air gap line,

X_d (unsaturated) $= 0.970$

Hence

$$x_m = X_d - x_a = 0.865$$

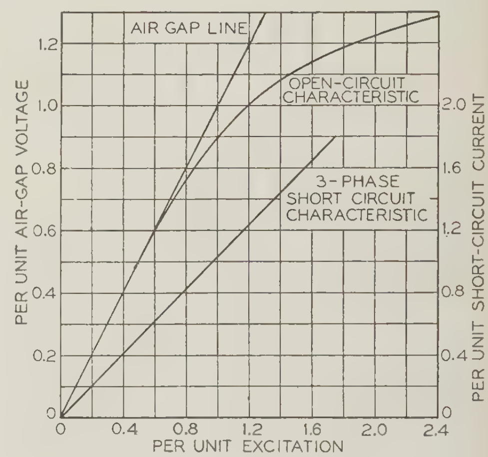
By equation 2,

$$x_s = 0.105 + \frac{0.865}{k}$$

Figure 4 shows x_s plotted as a function of E_a.

Consider this machine supplying power to an infinite bus through a feeder of resistance $r_e = 0.092$ and reactance $x_e = 0.436$, both expressed in per unit on the machine rating as a base. Let it be required

Fig. 3. Open-circuit and short-circuit characteristics of a cylindrical rotor synchronous machine



to calculate the power-angle characteristics of the system at a constant excitation, $E_f = 1.61$, and a constant receiver bus voltage, $V = 1.00$.

It will first be necessary to calculate the auxiliary curves of figure 5. The following calculation for one assumed value of E_a illustrates the method:

$$r = r_e + r_a = 0.114$$

For $E_a = 1.00$,

$k = 1.19$, $x_s = 0.830$, from figure 4

Hence

$$x = x_e + x_s = 1.27$$

Since r is small compared with x,

$Z = \sqrt{r^2 + x^2} = x$, very nearly, $= 1.27$
$Z^2 = x^2$, very nearly, $= 1.61$
$kZ = 1.51 \quad (kZE_a)^2 = 2.28$

However, r is sufficiently large so that α cannot be neglected.

$\alpha = \tan^{-1}(r/x) = 5.1$ degrees

By carrying through the above calculations for several other assumed values of E_a, data can be calculated for the auxiliary curves of figure 5.

In connection with these curves, equation 8 must

be used. For the case under consideration, $x_a + x_e = 0.541$. Hence

$$Z_c = \sqrt{(r_e + r_a)^2 + (x_e + x_a)^2} = 0.553$$

$$\alpha_c = \tan^{-1}[(r_e + r_a)/(x_e + x_a)] = 11.9 \text{ degrees}$$

Hence equation 8 becomes:

$$(kZE_a)^2 = 1.54 + 1.54 \cos(\delta - 11.9 \text{ degrees}) \tag{8a}$$

(It is, of course, pure coincidence that the constant term 1.54 in equation 8a is also the coefficient of the variable term.)

By assuming various values of δ, the corresponding values of P_a and P_b can now be calculated and data obtained from which the power-angle characteristics shown in figure 6 can be plotted. The following calculation for one assumed value of δ illustrates the method:

For $\delta = 60.0$ degrees,
$(kZE_a)^2 = 2.57$, from Equation 8a

Hence

$kZ = 1.54$, $\alpha = 5.2$ degrees, $Z^2 = 1.55$, from figure 5

Hence, from equations 6 and 7 at $\delta = 60.0$ degrees

$P_a = 0.980 \quad P_b = 0.876$

Figure 6 also shows a comparison of calculated with test results. The agreement is well within the accuracy required in most engineering problems, the calculated values of power being, at the worst, about 0.02 per unit below the test results.

Calculation of Maximum Power

Consider the system of figure 1. If in equation 6, (kZ) and α were constants, then under specified conditions of constant excitation and infinite bus volt-

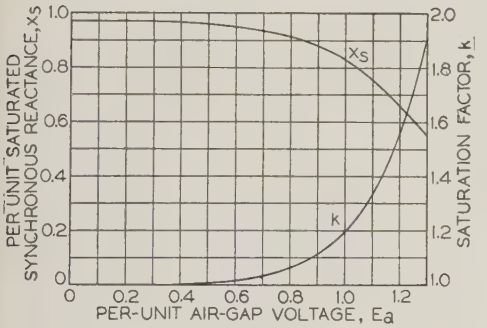


Fig. 4. Saturation factor and saturated synchronous reactance as functions of the air gap voltage

age, the air-gap power-angle characteristic would be a displaced sinusoid, and the maximum value of P_a would obviously be

$$\pm P_a \text{ max.} = \pm \frac{E_f V}{kZ} + \frac{E_f^2 r}{(kZ)^2} \tag{9}$$

and would occur when $(\delta - \alpha) = \pm 90$ degrees, the positive signs being for generator, and the negative signs for synchronous motor action of the machine. However, the saturation varies with changes in δ, and consequently (kZ) and α are variables dependent upon δ. Thus the air-gap power-angle characteristic is not exactly a displaced sinusoid, and the maximum

Table I—Comparison of Results Obtained by Various Methods of Calculating Maximum Power

	Case 1		Case 2		Case 3		Case 4	
Method	$P_a$max.	%error	$P_a$max.	%error	$P_a$max.	%error	$P_a$max.	%error
A	1.24	0	1.32	0	1.56	0	1.92	0
B	1.24	0	1.30	− 2	1.55	−1	1.91	− 1
C	1.29	+ 4	1.50	+14	1.70	+9	1.94	+ 1
D	1.16	− 6	1.26	− 5	1.44	−7	1.71	−11
E	1.45	+17	1.56	+18	1.46	−6	3.04	+58

value of the air gap power will not occur exactly when $(\delta - \alpha) = \pm 90$ degrees. However, in all practical cases, near its maximum value, the power-angle characteristic is approximately a displaced sinusoid and very little error will result from assuming that at $(\delta - \alpha) = \pm 90$ degrees, the corresponding value of P_a given by equation 9 is the maximum value. The error will not be over one per cent if the load angle at which the air gap power actually reaches its maximum value is within about 8 degrees of $(\delta - \alpha) = 90$ degrees. In equation 9, (kZ) is dependent upon the saturation. Its value at pull-out can be determined by substituting $\delta = (\pm 90 \text{ degrees} + \alpha)$ in equation 8, and referring to the auxiliary curve of (kZ) as a function of $(kZE_a)^2$, similar to that shown in figure 5.

Similarly, from equation 7, the maximum power which the machine of figure 1 can deliver to the receiver bus under specified conditions of constant excitation and receiver bus voltage is, very nearly,

$$P_b \text{ max.} = \frac{E_f V}{kZ} - \frac{V^2 r}{Z^2} \tag{10}$$

at a load angle $\delta = 90$ degrees $- \alpha$. The values of (kZ) and Z^2 to be used in equation 10 can be determined by substituting $\delta = 90$ degrees $- \alpha$ in equation 8 and referring to the auxiliary curves of figure 5.

Numerical Example 2

Consider the system of example 1, shown in figure 1. Let it be required to calculate the pull-out power of the generator at a constant voltage of the receiver bus, $V = 1.00$, and a constant excitation, $E_f = 1.61$ (as given in "Example 1").

Pull-out will occur approximately when $\delta = (90$ degrees $+ \alpha)$. The angle α is a variable dependent

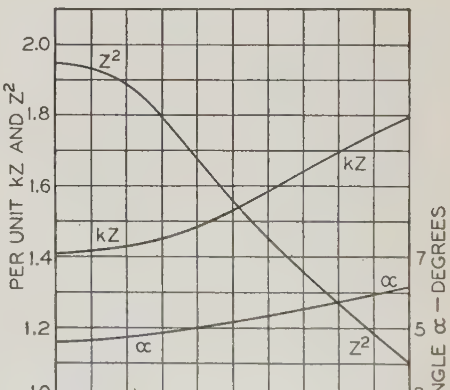


Fig. 5. Auxiliary curves for example 1

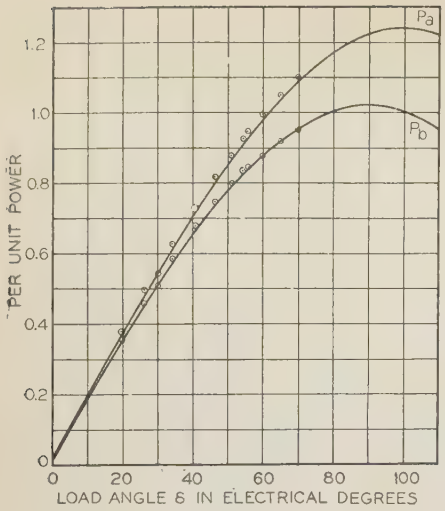


Fig. 6. Calculated power-angle characteristics of the system of example 1

Test points shown by small circles

upon saturation, and hence its exact value is not known. However, α is small and its approximate value will be accurate enough, say $\alpha = 5$ degrees. Hence, at pull-out, $\delta = 95$ degrees. Hence, from equation 8a, $(kZE_a)^2 = 1.73$ and from figure 5, $(kZ) = 1.46$. Hence from equation 9, P_a max. $= 1.24$. This checks to within slide rule accuracy the maximum value read from the complete air-gap power-angle characteristic shown in figure 6.

Table I shows a comparison of the maximum values of the air gap power calculated for several representative cases by the following methods of calculation:

Method A. From peak value of the air-gap power-angle characteristic calculated as shown in example 1.
Method B. Calculated by equation 9, as shown in example 2.
Method C. Neglecting saturation entirely.
Method D. Adjusted synchronous reactance, as described in reference 1 of the list at the end of the paper.
Method E. Adjusted synchronous reactance, as described in reference 2.

The results are shown for the following cases:

Case 1. System described in example 1.
Case 2. System of figure 1. Machine of example 1.
$r_e = 0.482$, $x_e = 0.661$, $V = 1.00$, $E_f = 1.70$ (Large resistance).
Case 3. System of figure 1. Machine of example 1.
$r_e = 0$, $x_e = 0.500$, $V = 1.00$, $E_f = 2.50$ (Large field current).
Case 4. Machine of example 1 directly connected to an infinite bus. $V = 1.04$, $E_f = 1.74$.

Method A is based directly upon the fundamental vector diagram of figure 1, which is known to give reasonably accurate results, as shown for case 1 by the comparison of calculated and test results in figure 6. Hence the results obtained by method A can be accepted as substantially correct, and these results used as a standard of comparison in judging the accuracy of the other methods. On this basis, the errors of the other methods are shown in table I.

Table II shows a comparison of the values of the synchronizing power, $dP_a/d\delta$, for the system of example 1 under the following load conditions: Generator delivering its rated kilovoltamperes with its excitation adjusted so that its terminal voltage $V_t = 1.00$. Receiver bus voltage $V = 1.00$. From these data, the following quantities which are required can be calculated: $E_a = 1.03$, $E_f = 1.61$, $P_a = 1.02$, armature current lags terminal voltage by 1.0 degrees.

The results were calculated by the following methods:

Method F. From slope of experimentally-determined air-gap power-angle characteristic, figure 6.
Method G. From slope of air-gap power-angle characteristic calculated as in example 1, figure 6.
Method H. Neglecting saturation entirely.
Method I. Equation 24 of reference 5 of the list at the end of the paper.
Method J. Reference 3.

Table II—Comparison of Results Obtained by Various Methods of Calculating Synchronizing Power

Method	$dPa/d\delta$	% error
F	0.653	0
G	0.647	− 1
H	0.741	+13
I	0.549	−16
J	0.749	+15

Summary

It is important to take into account correctly the effects of saturation in calculating the performance of synchronous machines. It is shown in this paper that these effects can be correctly and conveniently taken into account by means of equations 2 and 3 as expressions for the saturated synchronous reactance and excitation voltage of a cylindrical rotor synchronous machine operating under balanced steady-state conditions.

Appendix A—Derivation of Equation 8

From figure 1:

$$\bar{E}_a = \bar{V} + \bar{I}\,\bar{Z}_c \text{ and } \bar{I} = \frac{\bar{E} - \bar{V}}{\bar{Z}}$$

in which all quantities are expressed as vectors.

$$\bar{Z} = r + jx = (r_e + r_a) + j(x_e + x_a + x_m/k)$$

$$\bar{Z}_c = (r_e + r_a) + j(x_e + x_a)$$

Hence

$$\bar{E}_a = \bar{V} + \frac{(\bar{E} - \bar{V})\bar{Z}_c}{\bar{Z}} = \frac{\bar{E}\bar{Z}_c + \bar{V}(\bar{Z} - \bar{Z}_c)}{\bar{Z}}$$

Since

$\bar{E} = \bar{E}_f/k$ (equation 3), and $(\bar{Z} - \bar{Z}_c) = jx_m/k$,

$$\bar{Z}\bar{E}_a = \frac{\bar{E}_f}{k}\bar{Z}_c + j\,\bar{V}\,\frac{x_m}{k}$$

Hence

$$k\bar{Z}\bar{E}_a = \bar{E}_f\bar{Z}_c + j\bar{V}x_m \tag{11}$$

Let $\bar{V}$ be the reference vector. Then in polar form, $\bar{V} = V\underline{/0}$ degrees and $\bar{E}_f = E_f\underline{/\delta}$, where the symbols V and E_f (without the bars above them) mean the magnitudes of the voltages. In polar form $\bar{Z}_c = Z_c\underline{/90 - \alpha_c}$, where $Z_c = \sqrt{(r_e + r_a)^2 + (x_e + x_a)^2}$ and $\alpha_c = \tan^{-1}[(r_e + r_a)/(x_e + x_a)]$. Then in polar form, equation 11 becomes:

$$k\bar{Z}\bar{E}_a = E_fZ_c\underline{/\delta + 90 \text{ degrees} - \alpha_c} + Vx_m\underline{/90 \text{ degrees}} \tag{12}$$

The right-hand side of equation 12 is the sum of 2 vectors, the angle between them being $(\delta - \alpha_c)$. Their vector sum is the included diagonal of a parallelogram. Hence the magnitude of their resultant is given by:

$$(kZE_a)^2 = (E_fZ_c)^2 + (Vx_m)^2 + 2E_fVZ_cx_m \cos(\delta - \alpha_c)$$

where the symbols Z and E_a (without the bars above them) mean the magnitudes of these quantities. This is equation 8.

References

1. Adjusted Synchronous Reactance and Its Relation to Stability, H. B. Dwight. *Gen. Elec. Rev.*, v. 35, Dec. 1932, p. 609.

2. Discussion by G. C. Dahl of reference 3. Elec. Engg., v. 53, April 1934, p. 604–5.

3. Equivalent Reactance of Synchronous Machines, S. B. Crary, L. A. March, and L. P. Shildneck. Elec. Engg., v. 53, January 1934, p. 124–32.

4. Discussion by C. Kingsley, Jr., of reference 3. Elec. Engg., v. 53, April 1934, p. 603.

5. Synchronizing Power in Synchronous Machines Under Steady-State and Transient Conditions, H. V. Putman. A.I.E.E. Trans., v. 45, 1926, p. 1116–24.

6. Principles of Alternating Current Machinery, R. R. Lawrence. McGraw-Hill Book Company, 2nd ed., chapter V, p. 84–9.

A New Source of "Kilocycle Kilowatts"

Many applications of "kilocycle kilowatts" (electric power at frequencies of 1,000 to 100,000 cycles per second) have not been feasible because of the high cost of equipment for generating such power. In this paper, a new source of kilocycle power employing an electronic tube called the arc tube is described. The cost of the arc tube and its associated equipment is lower than that of other sources of kilocycle power; its frequency is readily adjustable.

By
L. D. MILES
ASSOCIATE A.I.E.E.

General Elec. Co.,
Schenectady, N. Y.

Manufacturers continually are finding that an optimum frequency exists for doing most high frequency jobs. The comparatively high initial cost of equipment for generating kilocycle frequencies (1,000 to 100,000 cycles per second), however, has prevented both industrial use of kilocycle frequency power and experimentation to determine optimum frequencies. This paper reviews a few present-day uses of "kilocycle kilowatts" and suggests the arc oscillator tube as a source of kilocycle frequency power available at lower cost than the usual type of equipment.

A paper recommended for publication by the A.I.E.E. committee on general power applications. Manuscript submitted June 6, 1934; released for publication Nov. 14, 1934.

The fact that high frequency power is useful industrially and that best frequencies exist for most processes is best established by citation of some present uses: 360 cycle power is used to bake enamel on auto fenders; 1,000 to 2,000 cycle power is used for metal and scrap melting; 900 to 2,000 cycle power excels for certain alloying processes inasmuch as electrical stirring occurs and can be controlled by frequency; 4,800 cycle power is found best in the manufacture of razor blade steel; 5,000 cycle power is used in ozone generators; 30,000 cycle power is optimum for proximity pipe welding; 40,000 to 50,000 cycle power is used in small induction furnaces; and 50,000 cycle power is used to sterilize milk.

Characteristics of Power Sources

There are 3 types of apparatus in common use for securing kilocycle frequency power: (1) rotating equipment, (2) high vacuum tubes and equipment, and (3) gaseous tubes and equipment. The industrial utility of each is governed principally by initial cost, operating cost, efficiency, life, input voltage requirements, size, and weight.

Rotating equipment is expensive, its operating costs are reasonably low, its efficiency is fair, its life good, it can be built for industrial supply voltage, it requires a good foundation, and is rather heavy.

High vacuum tube equipment is expensive, its operating costs are low, its efficiency fair, and its life fair. A rectifier must be built into the unit as high direct voltages usually are required. Complete equipment is rather bulky, but weight is light.

Gaseous tube equipment has moderate initial and operating costs for installations of 1,500 cycles per second or less; above 1,500 cycles costs mount

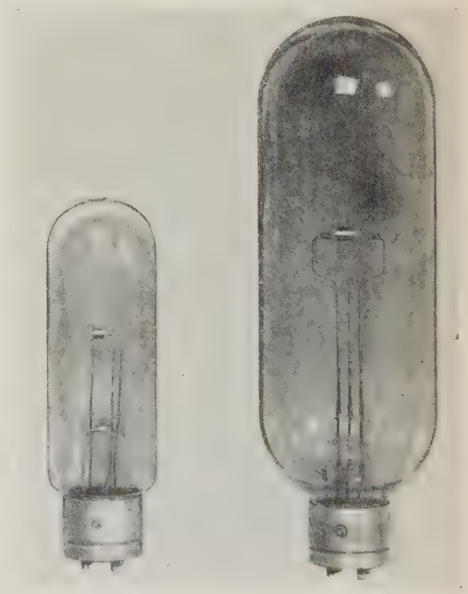


Fig. 1. Two typical arc oscillator tubes: (left) 50 watts and (right) 500 watts output

with frequency. Efficiency is good, and life is fair. Industrial direct voltages may be used on the newer tubes. Space requirements and weight are moderate.

In any of these systems, operating costs, efficiency, and life are reasonable, but the principal curtailment to general use is high initial cost. However, a fourth source of high frequency power, the arc tube, presents to industries a source of kilocycle frequency power at lower initial cost.

In addition to low initial cost, it is characterized by low operating costs, fair efficiency, fair life, operation on industrial direct voltages, simplicity, small space, and small weight requirements.

Arc Tube Equipment

The arc tube consists essentially of 2 electrodes closely spaced in inert gas under high pressure. Figure 1 shows 2 typical tubes rated at 50 and 500 watts output, respectively. The well designed and built arc tube has 3 outstanding points of superiority over the old open arc, which predict its popularity: (1) an optimum gas pressure may be used to give maximum power; (2) electrodes may be spaced permanently for maximum efficiency at rated output; and (3) oxygen and water vapor may be driven from the tube before inert gas is admitted, thus insuring uniform power, better efficiency, and longer life.

Besides the tube, essential equipment consists of a choke coil, a stabilizing resistor, a capacitor, and an

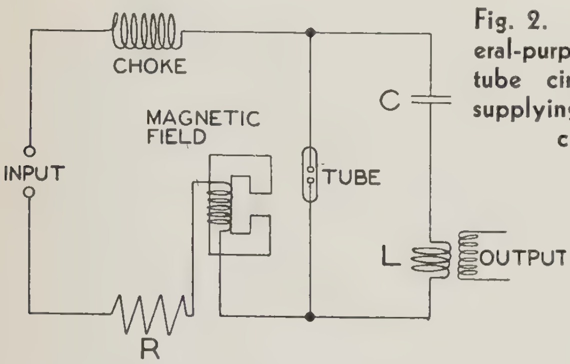


Fig. 2. A general-purpose arc-tube circuit for supplying kilocycle power

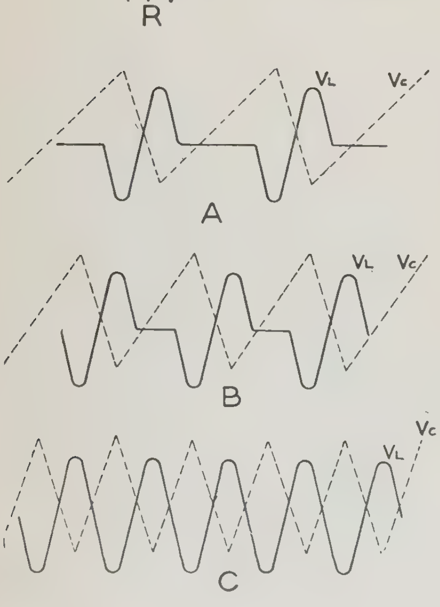


Fig. 3. Wave shape of output of circuit shown in figure 2

V_C—Voltage across capacitor C
V_L—Voltage across conductor L
A—Output for slow charging rate of capacitor C
B—Output for faster charging rate
C—Sine wave output for optimum charging rate

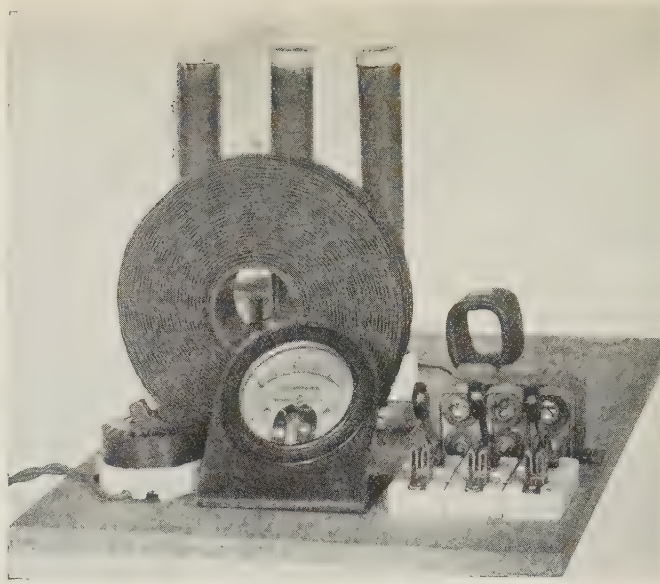


Fig. 4. A 50-watt arc-tube oscillator

inductor. In high power applications the stabilizing resistor may take the form of the ohmic resistance of the windings of an electromagnetic field.

The optimum circuit arrangement depends upon the type of load, the wave shape, and the frequency desired. One general-purpose circuit is illustrated in figure 2. The choke maintains uniform continuous-current input, while high frequency oscillations take place in the branch of the circuit that contains the inductor L and the capacitor C, or the "LC-tube" circuit.

A complete cycle of operation may be described as follows:

1. When voltage is applied, capacitor C is charged through resistor R. (The choke causes a momentary pause in the starting cycle but not thereafter, as it maintains a steady continuous current during operation.)

2. The tube conducts no current until capacitor C is charged to sufficient voltage for breakdown between tube electrodes. At this point the tube ionizes, acts as an instantaneous short circuit, and allows C to discharge through the "LC-tube" circuit. Line current inrush is prevented by the choke.

3. At the instant C is completely discharged, a high current is flowing in the "LC-tube" circuit. The inductor L continues current flow, which overdischarges the capacitor and drives the tube voltage negative, whereupon the arc extinguishes and the tube is again an open circuit.

4. The capacitor C again becomes charged through the resistor R and the cycle is repeated.

Output at any desired voltage may be taken from the secondary of a transformer which constitutes the inductor; or, as in induction heating, output is taken directly from the inductance coil, which is the furnace coil. Output is in the form of sinusoidal pulses caused by each capacitor discharge (see V_L in figure 3). Frequency of these pulses is governed by the capacitor charging rate; the effect of successively decreasing the capacitor charging period is shown in figure 3. Part C of figure 3 shows that if charging periods are made short enough, sinusoidal pulses of voltage appear in uninterrupted sequence, giving sine wave output.

Variable frequency is accomplished by changing

either the period of charge, or the periods of both charge and discharge of the capacitor. A change in the value of either the stabilizing resistance or the voltage alters the period of charge; changes in load or inductance alter the period of discharge; change of capacitance alters both periods. Optimum sine wave operation at different frequencies obviously requires proportionate changes in charging and discharging periods. Sine wave operation may be obtained at any frequency by fixing 2 constants such as, input voltage and inductance, capacitance and inductance, or—the more usual—input voltage and load, and choosing other constants accordingly.

Wider Use of Kilocycle Power Predicted

The arc tube is destined to supply cheaper power for industrial utilization because: First, it is adaptable to varying needs—frequency can be changed conveniently; second, equipment can be made economically in any reasonable size, either to supply only a few watts or to furnish 50 or more kilowatts; third, arc tube equipment operates directly from industrial direct voltages; fourth, there are no moving parts to wear, and operating costs and maintenance are low; fifth, little associated apparatus is required; sixth, tube construction is not complicated, and hence with reasonable production cost should be low.

With "kilocycle kilowatts" available at lower cost, the use of 1,000 to 100,000 cycle power in industry, which has been limited to the few known processes that justify the present cost of such power, should increase. Some new applications that have been awaiting the availability of cheaper kilocycle power can now be put into practice, and doubtless further uses will be found by the experimenter who can use the less expensive equipment.

Precise Speed Control for D-C Machines

By
R. H. FRAZIER
MEMBER A.I.E.E.
Mass. Inst. o Tech., Cambridge

J. EISLER
ASSOCIATE A.I.E.E.
Mass. Inst. of Tech., Cambridge

W. P. FRANTZ*
ASSOCIATE A.I.E.E.
Curtis Publishing Co. New York, N. Y.

In this paper a circuit is described that holds the average speed of a d-c shunt-wound machine as constant as the standard reference used (for which the most precise standard known can be employed) and holds the instantaneous speed very close to standard speed if there are not sudden changes of load or applied voltage. The machine is positively indexed in phase with respect to the standard. In addition to its precision, the method is characterized by its simplicity and general applicability over a considerable part of the range of d-c machine speed and capacity.

To meet a need for supplying several amperes of alternating current of fixed wave form, with amplitude and frequency held constant to 1 part in 2,000 or better, the method of speed control described in this paper was developed; this need arose in connection with a new method for the precise determination of specific heats of metals.[1,2,3,4]

The method of speed control devised proved to be so much more precise than is needed for the particular problem at hand, and to be of such simplicity and general applicability that it has been considered worthwhile to report on the scheme apart from the project for which it was developed. In the problem at hand the immediate object was to produce something that would serve the purpose sufficiently well, with a minimum expenditure of time and money. Hence (as is pointed out later) some few refinements that could be added very readily to an installation designed to operate indefinitely have not been incorporated. Many circuits were tried without finding another that operated as satisfactorily as the one described. A complete account of this evolution to the final form cannot be included here, but a record is on file at the Massachusetts Institute of Technology.[5]

Factors Affecting Speed of a Shunt Machine

As a preliminary to explaining the operation of the speed control circuit, it may be advantageous to

A paper recommended for publication by the A.I.E.E. committee on instruments and measurements. Manuscript submitted April 13, 1934; released for publication Dec. 31, 1934.

1. For all numbered references see list at end of paper.

* Formerly graduate student, department of electrical engineering, Massachusetts Institute of Technology, Cambridge.

enumerate the factors that tend to cause the speed of a shunt wound machine to change:

1. Those causing gradual change.

a. Change in temperature of the windings.
b. Gradual change of applied voltage.
c. Gradual change of load.
d. Gradual change of friction (including windage).

2. Those causing sudden change.

a. Sudden change of applied voltage.
b. Sudden change of load.
c. Sudden change of friction (such as might result from axial oscillation).
d. Poor armature brush contact; erratic sparking.

The method explained in this paper keeps the machine synchronized with a standard in spite of all of the gradual changes however great (within the limits of the design of the machine) with entire success, and likewise for all the sudden changes if they are not large. Large sudden changes of applied voltage or load are permissible if pronounced hunting about the index position is permissible. Factors 2*c* and 2*d* ordinarily are small and largely can be avoided.

The method is such that the machine is positively indexed in phase with a frequency standard (which can be of the utmost precision if desired) so that as long as there are no sudden changes too large for the control to handle, the average speed of the machine is as constant as the frequency of the standard. If sudden changes are absent (as in the particular problem at hand) the speed of the machine is at every instant equal to (or a constant multiple of) the frequency of the standard to an extremely high degree of precision.

Machine Used

The machine for which the circuit was developed is a Roth Brothers Company single-phase synchronous converter the name plate data and resistances of which are as follows:

Power	500	watts
Voltage	115	volts d-c
	75	volts, 60 cycles per second
Current	7.2	amperes a-c
Speed	1,800	rpm
Armature resistance	1.0	ohm between d-c brushes
Field resistance	270	ohms

The converter is operated inverted from a storage battery to supply alternating current at about 62 cycles per second (in order to avoid interference from the 60 cycle supply in the building). It is provided with a flywheel which brings the total moment of inertia of the rotating parts to about 4 pound-(feet).[2] The inductance of the field winding (ignoring external resistance in series) is such that about 0.7 second is required to build up from zero to about 70 per cent of normal current. (What really is of most significance here is the time required to change the flux a small amount near its normal value. These figures are given merely to indicate the order of magnitude of the field response time.) The converter and its speed control circuit are shown diagrammatically in figure 1.

Operation of Circuit

The tuning fork standard F is housed in a thermally-insulated electrically-heated box in which air is circulated by means of a fan, and is kept within several hundredths of a centigrade degree of a fixed temperature by means of a Wheatstone bridge thermostat arrangement not shown. The frequency supplied by the fork can be adjusted over a moderate range in the vicinity of 60 cycles per second by means of sliding weights. The fork is started by tapping key K, thus energizing the fork driving coil. When the fork contact is made, the grid of tube T_1 (a grid-controlled mercury-vapor-filled tube) is made sufficiently positive to "trip" the tube. An instant later, the discharge in T_1 is extinguished by the discharge of condenser C_1. The time constant of the circuit used to change the potential of the grid is so small that in the meanwhile the potential of the grid has dropped below the tripping potential, so that the tube cannot trip again until the fork contact closes again. Thus the action of tube T_1 accomplishes the driving of the fork and the flashing of the neon tube N connected to the secondary of an induction coil S (the vibrator of which is clamped down). The disc D, attached to the converter shaft, when viewed by the light from the flashing neon tube gives visual evidence of the speed of the converter with respect to the frequency of the fork. This stroboscope circuit was adapted from one suggested by Professor H. E. Edgerton, Massachusetts Institute of Technology.

The part of the circuit described thus far is in the main merely auxiliary to the speed control circuit *per se*, which operates as follows: On the converter shaft is mounted also a 2-part commutator C, about 7 inches in diameter. The segments are separated by about $^1/_{16}$ inch of insulation. Two brushes are about 180 degrees apart, and a third brush is midway between them. The potential of the third or middle brush is controlled in a manner similar to that for the grid of tube T_1; it becomes positive at the instant the fork contact is made, but then falls in potential with extreme rapidity. If

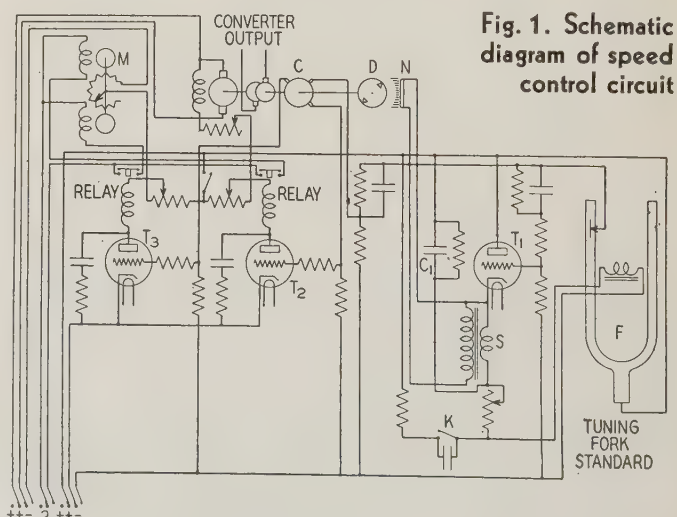


Fig. 1. Schematic diagram of speed control circuit

1 and 3, 230 volt batteries; 2, 115-volt 60-cycle supply

Table I—Check of Converter Frequency Against Pendulum

Run	Temperature in Fork Box, Degrees C	Total Cycles	Pendulum Beats*	Converter Frequency*
1	36.05	36,000	583.33	61.715
2	36.05	48,600	787.50	61.714
3	36.05	37,800	612.45	61.719
4	36.05	75,600	1,224.89	61.720
5	36.05	73,800	1,195.90	61.711
			Weighted average	61.716

* The pendulum does not beat exactly seconds. However, its calibration in terms of seconds does not enter into the determination of how constant the speed of the converter was held. The only questions entering here as far as the pendulum is concerned are the effects of change in the pull of gravity, the length of the pendulum, the amplitude, and the damping. The total possible effect of these factors under the circumstances of the test can be shown to be negligible within the precision obtained. In order to obtain frequency in cycles per second, the last column must be multiplied by 1.00063 ± 0.00005.

when the middle brush becomes positive it is on the insulation between segments, nothing further happens, and as long as this continues the converter is perfectly synchronized with the fork. If, however, the middle brush is on one segment or the other at the instant it becomes positive, either tube T_2 or T_3 "trips" (both of which are grid-controlled mercury-vapor-filled tubes), thus supplying a small pulse of excitation to the converter in the direction needed to keep the speed correct. The maximum value of the pulse is reached in about 0.005 second whereupon the discharge in the tube (T_2 or T_3) is extinguished by condenser discharge. The pulse then dies out as the extinguishing condenser acquires its charge, and may be succeeded by another pulse the next time the fork contact is made if the rotor has not been returned to the index position.

The scheme as outlined to this point controls the speed of the machine quite satisfactorily for a while; but as the field temperature increases or the supply voltage for the converter drops, the machine tends always to go faster or always to go slower than the standard speed. Hence, if the amount of control that tube T_2 and T_3 exert is initially small enough to produce negligible hunting, the control eventually is lost, while if it is made powerful enough to retain synchronism in spite of large changes of field temperature or of supply voltage, undesirable hunting is produced.

The feature that solved the foregoing difficulty, and that is mainly responsible for making possible the smooth continuous operation of the machine indefinitely in the absence of substantial sudden disturbances, is the motor-driven field rheostat M. As the machine tends to change speed gradually for any reason whatever, one of the tubes T_2 or T_3 is in operation a greater fraction of the time than the other. By means of the relays in series with the respective tubes, the rheostat M is adjusted gradually by one or the other self-starting synchronous clock motors pinned to its shaft. The combination of grid-controlled mercury-vapor-filled tube and automatic rheostat control makes it possible to reduce the tube control to a very small amount and yet keep the machine synchronized. The motor driven rheostat gradually changes the field current so that the machine always is naturally trying to run practically in synchronism with the tuning fork. The control tubes then need only give occasional small quick pulses to keep the field rheostat properly adjusted and to correct for small sudden disturbances. The pointer on the stroboscope disc in fact practically never changes its position by more than 1 mechanical degree, and ordinarily drifts slowly within an angle of about $^1/_2$ a mechanical degree; the control tubes "trip" only at intervals of several seconds after the machine is near temperature equilibrium. Under these circumstances the instantaneous speed may differ from the average speed by 1 part in 10,000 or 20,000.

Converter Frequency Checked

The results of 5 runs checking the frequency of the converter against a pendulum are shown in table I. Since in these runs the rotor always was practically exactly in synchronism with the tuning fork (as indicated by the stroboscope) the runs are in reality checks on the constancy of the frequency of the standard. While it is fully evident to any one who can view the machine in the light of the stroboscope that the machine will not retain so constant a speed over a period of 10 to 20 minutes without the use of the control circuit even if the machine is energized from a large, independent battery, a few tests were made to determine the variation. The results are given in appendix *A*.

From table I it is found that the maximum deviation from the average is 5 parts in 60,000 of which about 2 parts can be charged against the method of test used. A contact-making synchronous clock motor run from the converter was used to record on the tape of a chronograph the number of cycles through which the converter rotated. The pendulum made a time record on the same tape. This record could not be read closer than 0.01 second, and small irregularity in the gear train of the clock motor probably could account for another 0.01 second. The average deviation of the 5 runs is 3 parts in 60,000, and the probable error of the average is about 1 part in 60,000. The most probable frequency of the converter when run under the conditions of the tests is 61.755 ± 0.003 cycles per second, most of the uncertainty here being attributable to the fact that the pendulum is calibrated to only 1 part in 20,000. Several runs taken with the fork box at lower temperatures indicate that the fork has a temperature coefficient of approximately 0.01 per cent per degree centigrade. Whatever portions of the difference between the results for the various runs are chargeable to actual difference in frequency of the fork most likely are caused by slight differences in amplitude resulting from slight changes of battery voltage, or from a slight change of impedance of the driving coil circuit.

Power Sources Required

The circuit as used and as described requires 2 independent direct current sources. However, the source for the control tubes need not be a battery. It is preferable to have tube T_1 on a steady voltage

to avoid possible change of amplitude of the fork, but its circuit could be operated from the same source as the converter. Neither is it a requisite to have both 115 and 230 volts to supply the tubes. The latter is used on tube T_1 to get a brighter flash from the neon tube. The circuits for tubes T_2 and T_3 are different from the circuit for T_1 because the arrangement saves one filament transformer (none of which is shown) and because the control tubes are of a type slightly different from tube T_1. The only reason for using different types is to use those at hand; either type works at any of the positions, as might other types.

The separate source for the control tubes could be eliminated entirely in one of several possible ways. Instead of passing the tube currents through portions of the resistance in the field circuit, the tubes might operate relays that would respectively insert or short-circuit resistance in the field circuit. However, this scheme might not be as quick acting as the scheme used, and would be limited by the current breaking capacity of contacts. A separate control-field winding might be used. This has the disadvantage of requiring a specially wound machine, but has the advantage of affording quicker response in change of flux than can be expected from the main field winding. Also, there are other schemes, which the authors are developing, whereby the plate supply for the control tubes may be obtained from the alternating current output of the converter (when such load is not objectionable) through an insulating transformer.

It is not vital to have a voltage supply double the normal machine voltage, for the shunt field. The double voltage is used across the field circuit because it is available and has the advantage of making it possible practically to cut in half the time required to build up field flux, and to cut in half the effect of change in resistance of the field winding. Neither is it necessary to have a separate alternating current supply. Unless such load is objectionable, the filament transformers could be energized from the converter output; otherwise filament batteries could be used. Likewise the power for the field rheostat drive could be supplied from the converter output, or from a direct current source.

Self-starting synchronous clock motors are used for the field rheostat drive merely because of their availability, convenient gearing, and adequate torque. The 2 motors are coupled to the same gear train in such a way that one serves for each direction of rotation. A single small reversible motor really should be used. It is conceivable that for small machines, field rheostat motors could be driven directly in series with the control tubes, thus eliminating the relays. The range and speed of control obtainable from this rheostat is very flexible because the rheostat can be extended indefinitely in range and can be operated at any desired rate of change of resistance merely by proper design of the rheostat or an accompanying shunt, and by selection of speed and gearing for the driving motor.

It is conceivable that with a certain amount of study and experiment the design could be carried further to enable the machine to meet larger sudden changes of load or voltage without large swings from the index position, and without continual oscillation about the index position resulting from the increased control necessary to meet these larger changes, when large sudden changes are absent. In the circuit described, the maximum current from the control tubes is about 0.05 ampere, and passes through only about 4 to 20 ohms of the field circuit, while the normal field current is about 0.4 ampere in a circuit of about 600 ohms resistance. Hence it readily is seen that the amount of tube control actually used in comparison with the maximum that could be obtained is extremely small. This aspect of the problem has not been given much attention, however, because of the necessity of pushing along the work for which the particular development serves. A study now has been started with the specific purpose of developing a circuit that will retain the machine in synchronism and give a minimum of hunting trouble in spite of substantial sudden changes of load or voltage. It is emphasized that such claim is not made for the circuit herein described. Some data concerning the performance of this circuit when sudden changes occur is given in appendix *B*.

The commutator is of copper, not particularly carefully machined, but has given very little trouble. Light strips of phosphor bronze were used for brushes at first, but were discarded because they "tore up" the commutator too much. Pencil leads have been used very successfully but the softer leads gradually left a deposit that made it necessary to provide the commutator with wipers in order to prevent short-circuiting of the segments across the insulation. There are other commutator and brush arrangements that will avoid this; however, brushes made from thin 6*H* pencil leads have been in use for some time without wipers with entire success, and look as if they would last a long time. Two leads are used in parallel in each holder. With a wide smoothly-ground commutator, using a row of brushes in each holder, the utmost reliability could be obtained, and the brushes could be replaced without interrupting operation. In fact, in the holders diametrically opposite each other there is no need at all for having the brushes narrow. Provided that the brushes are not made so heavy that a reasonable spring force will not keep them in contact with the commutator, they can be made wide, to reduce the rate of wear. The middle brush must be of such width that it does not short-circuit across the insulation, but allows a little dead space so that if the machine is running at the correct speed, it can drift a very small amount without being alternately accelerated and retarded unnecessarily. The presence of this small dead space adds greatly to the smoothness of operation.

For installations requiring extreme reliability, several control tubes could be used in parallel at each tube position and the design made so that one at each position still would be adequate. This would permit changing tubes without interrupting operation.

Since the precision with which the speed can be controlled depends practically entirely on the precision of the standard, the possible use of such a speed

control scheme to supply synchronous clocks where controlled central-station frequency is not available has been suggested. Various sorts of frequency standards could be utilized to accomplish what the tuning fork does if greater precision is desired, though according to E. Norrman[6] tuning forks can be made that rival quartz crystals as standards. It would be easy of course to avoid having a contact made by the fork itself, by using a magnetic pick-up coil, or a shutter intercepting a beam of light directed upon a photoelectric tube, for examples, and amplifying the output in either case so that another contact could be made to do what the fork contact does.

Probably there are other situations both commercial and experimental in which the scheme may be applicable, since there appears to be no reason why it could not be worked out over a considerable part of the range of speed and capacity of direct current machines.

The writers are indebted to the American Academy of Arts and Sciences for a grant from the Rumford Fund, a small part of which was used for purchase of apparatus for this development.

Appendix A—Tests Made Without Using the Control Circuit

The machine was started cold, synchronized with the tuning fork, and the control circuit then disconnected. The speed was checked during a 40 minute interval. The machine then was synchronized again with the tuning fork, and the control circuit again disconnected. The speed then was checked during a 15 minute interval. The machine then was synchronized again with the tuning fork and operated for more than 2 hours, at the end of which time the speed was checked over a 15 minute interval. The results were as follows:

Time, Minutes	Gain in Speed, Per Cent
0	0.00
10	0.55
20	1.08
30	1.50
40	1.75
41	0.00
56	0.28
172	0.00
187	0.19

These results were obtained with no load on the converter. A second test taken with normal specific-heat-test inductive load of about 0.8 ampere at 0.95 power factor gave substantially the same results. The gains in speed were computed from the apparent speed of the stroboscope disc averaged over 1 minute intervals; instantaneous changes in speed were substantially greater than shown, and in the last 15 minute interval some changes were negative. It is conceivable, of course, that after the machine is warmed up an interval might be selected wherein the number of revolutions lost would equal the number gained and that the average speed therefore would check exactly with standard speed, but such coincidence is extremely unlikely. The total number of revolutions gained were as follows:

Interval, Minutes	Revolutions Gained
0– 40	751
41– 56	24
172–187	18

These tests make it readily evident that through operating the machine from a battery and delivering a constant load, it is futile to hope for as nearly constant speed without the control circuit as with it, even for time intervals of several minutes. The steadiness of the speed, even after a delay of 3 hours was allowed for temperature equilibrium to be practically reached, compares unfavorably with the results obtained when the machine was synchronized with the fork; had a more precise standard been used the comparison would be still less favorable. If the machine were run continuously for a considerable time interval, the departures from standard speed caused by changes in ambient temperature and change in battery voltage between charging periods readily could become enormous in comparison with the tolerances acceptable for precise frequency standards.

Appendix B—Tests Involving Sudden Changes of Load or Voltage

It is emphasized again that the circuit described in this paper is not designed to withstand large sudden changes of load or voltage, but is designed particularly to control the machine with smoothness when operating from a battery supply and delivering a substantially constant load. However, as a matter of interest in order to obtain an idea of what this circuit can do when the load or the voltage is changed suddenly, the following tests were made.

A sudden change in voltage was obtained by suddenly throwing a load across or removing a load from the 230 volt terminals of the supply battery for the converter. This was tried with various loads of various power factors on the converter, with no significant differences. It was found that a sudden change of about 4 volts could be made across the 230 volt supply (giving about 2 volts change across the armature) without the rotor swinging more than 90 mechanical degrees from the index position, after which control is temporarily lost. In order to accomplish this, the control tube current was passed through 100 ohms of the field circuit, this being simpler than to increase the current which is limited by the relay coils. Under these circumstances the rotor oscillated continually about 6 mechanical degrees each side of the index position. It should be borne in mind that by increase of the control tube current it is possible further to strengthen the control excitation enormously without overloading the tubes, and so to withstand greater sudden changes, but the accompanying oscillations of the machine about the index position become objectionable.

With the control circuit the same as described in the preceding paragraph, the machine was operated for about $2^1/_2$ hours directly from the 115-230 volt laboratory supply from the power house (private plant of the Massachusetts Institute of Technology; voltage fluctuations are caused by sudden changes of laboratory or other loads). During this time a recording voltmeter showed maximum variation across the 230-volt lines (in the laboratory) of about 4 volts, with jumps of a few volts every minute or 2. It is likely that some transients were larger than recorded because of the sluggishness of the recorder mechanism. No recording instrument was available for the voltage to neutral. During the run the machine on 6 occasions gained or lost from $^1/_2$ to 5 revolutions before recovering synchronism; the net loss for the entire period was $4^1/_2$ revolutions.

The machine also was operated for several hours as the only load on a 250 kw generator driven from a 325 kva induction motor in the laboratory substation. The control tube current was passed through only 20 ohms of the field circuit (the maximum used for battery operation) and although the operation was not as smooth as for battery supply, synchronism never was lost.

A sudden change of resistance load was made across the output terminals of the converter (the control tube current passing through 100 ohms of the field circuit). It was found that a change of about 10 per cent of rated load could be made suddenly (starting from any or no previous load) without causing the rotor to swing more than 90 mechanical degrees from the index position. The normal specific-heat-test inductive load of about 0.8 ampere at 0.95 power factor could be thrown on or off with practically no disturbance at all, because of its demagnetizing effect, even with the control excitation much smaller. The changes of load taken from the machine were accompanied by changes of 0.5 to 1 volt across the armature terminals.

These tests leave little doubt as to the feasibility of withstanding

larger sudden changes by making the control excitation more powerful. It is necessary to modify the method of control, however, so as to avoid continual large oscillation about the index position.

References

1. A Precise Method for Determining the Thermal Diffusivity of Solids, R. H. Frazier. *Phys. Rev.*, v. 39, 1932, p. 515–24.

2. Further Data on the Thermal Diffusivity of Nickel, R. H. Frazier. *Phys. Rev.*, v. 40, 1932, p. 592–5.

3. A Precise Determination of the Thermal Diffusivity of Zinc, R. H. Frazier. *Phys. Rev.*, v. 43, 1933, p. 135–6.

4. Purity of Zinc for Which the Thermal Diffusivity Recently Was Reported, R. H. Frazier. *Phys. Rev.*, v. 43, 1933, p. 762.

5. The Development of a Method for Precise Speed Control of a Direct-Current Shunt-Wound Machine, W. P. Frantz. A thesis presented for master of science degree in electrical engineering, Mass. Inst. of Tech., Cambridge, 1934.

6. A Precision Tuning Fork Frequency Standard, E. Norrman. *I.R.E. Proc.*, v. 20, 1932, p. 1715–31.

Calculations for Coreless Induction Furnaces

Calculations of electrical characteristics of coreless induction furnaces usually are made by means of the penetration formula (equation 18 in this paper); this formula, however, gives only an approximation which is fairly accurate only at relatively high frequencies. As a wide range of frequencies can be used in these furnaces, there is a need for calculations that are good at any frequency; to meet this need, the fundamental calculations upon which the penetration formula is based are presented in this paper.

By

H. B. DWIGHT
FELLOW A.I.E.E.
Mass. Inst. of Tech., Cambridge

M. M. BAGAI*
ENROLLED STUDENT A.I.E.E.
Ampere, N. J.

A CORELESS induction furnace usually consists of a cylindrical coil wound rather closely on the outside of a crucible holding the molten charge. It is equivalent to a transformer with a solid metal secondary. Several formulas are available for calculating the electrical characteristics of this type of furnace, and it is useful to show the relation between these formulas, and the range for which each is suitable. This work has been taken up in connection with a thesis at Massachusetts Institute of Technology, and in this paper the formulas dealing with the Bessel function solution and the pentration solution for the current and flux in the charge are discussed.

In figure 1, let a be the average outside radius of the charge in centimeters and b the radius of the primary coil. Assume that conditions are uniform in the direction of the axis of the cylinder, that the coil and the charge are of equal axial length, and that the permeability of the charge is unity. If the permeability is not unity, then with alternating current and flux the permeability changes during every cycle, and the accuracy of a solution based upon the assumption of constant permeability is greatly reduced. If such an assumed constant value is adopted, the permeability μ is inserted as a multiplier along side of ω and f.

Let the magnetic flux density between the radii a and b be H_0, produced by the current in the primary coil. Circumferential currents will flow in the charge in the direction opposite of that of the primary current, and so the flux density within the charge will be less than H_0. If H be the flux density, and i the current density in the charge in abamperes per square centimeter, at radius r

$$H_0 - H = 4\pi \int_r^a i\,dr \tag{1}$$

Since H_0 is constant, by differentiating equation 1

$$\frac{dH}{dr} = 4\pi i \tag{2}$$

The total voltage around any circle of radius r due to resistive potential drop and alternating flux is zero. That is,

$$2\pi r i \rho_1 + j\omega \int_0^r 2\pi r(-H)dr = 0$$

the flux in the direction in which i would drive magnetic flux, being $-H$. The resistivity of the charge in abohms per centimeter cube is ρ_1.

Substituting the value of i given by equation 2, and multiplying by $2/\rho_1$,

$$r\frac{dH}{dr} - j\frac{\omega}{\rho_1}\int_0^r 4\pi r H dr = 0$$

Differentiating,

$$r\frac{d^2H}{dr^2} + \frac{dH}{dr} - j\frac{\omega 4\pi r}{\rho_1}H = 0$$

Put

$$p^2 = \frac{-j\omega 4\pi}{\rho_1}$$

$$\frac{d^2H}{dr^2} + \frac{1}{r}\frac{dH}{dr} + p^2 H = 0$$

A paper recommended for publication by the A.I.E.E. committee on electrochemistry and electrometallurgy. Manuscript submitted Sept. 4, 1934; released for publication Dec. 6, 1934.

* Formerly graduate student, Massachusetts Institute of Technology, Cambridge.

Let $pr = z$

$$\frac{d^2H}{dz^2} + \frac{1}{z}\frac{dH}{dz} + H = 0 \qquad (3)$$

This is the standard form of Bessel's differential equation of order zero. The solution consists of Bessel functions and is

$$H = AI_0(mr\sqrt{j}) + BK_0(mr\sqrt{j}) \qquad (4)$$

putting $pr = mrj\sqrt{j}$ where $m^2 = \frac{4\pi\omega}{\rho_1}$

Symbols A and B represent constants to be determined by the boundary conditions. The function K_0 contains log $(mr\sqrt{j})$ and so is infinite when r is zero. As the magnetic flux density cannot be infinite at the center of the metallic charge, the constant B is zero. The equation then becomes

$$\begin{aligned} H &= AI_0(mr\sqrt{j}) \\ &= AJ_0(mrj\sqrt{j}) \\ &= A(\text{ber } mr + j \text{ bei } mr) \text{ by definition} \end{aligned} \qquad (5)$$

Constant A is found by putting $r = a$ where $H = H_o$

$$A = \frac{H_o}{\text{ber } ma + j \text{ bei } ma} = \frac{4\pi NI_1}{l(\text{ber } ma + j \text{ bei } ma)} \qquad (6)$$

where

I_1 = primary current in abamperes
N = turns in the primary
l = axial length in centimeters

$$H = \frac{4\pi NI_1}{l}\frac{\text{ber } mr + j \text{ bei } mr}{\text{ber } ma + j \text{ bei } ma} \qquad (7)$$

The voltage impressed on the primary coil is $I_1R_{abs} + j\omega\varphi N$ where R_{abs} is the resistance in abohms of the primary coil to alternating current of the given frequency and φ is the total flux in the circle of radius b, neglecting the thickness of the primary winding.

$$\begin{aligned}\phi &= \int_{r=0}^{a} 2\pi r \frac{4\pi NI_1}{l}\frac{\text{ber } mr + j \text{ bei } mr}{\text{ber } ma + j \text{ bei } ma}dr + \int_{r=a}^{b} 2\pi rH_o dr \\ &= \frac{8\pi^2 NI_1 a}{lm}\frac{\text{bei}' \, ma - j \text{ ber}' \, ma}{\text{ber } ma + j \text{ bei } ma} + \pi(b^2 - a^2)H_o\end{aligned}$$

where the prime (′) denotes differentiation with respect to ma, using the integrals

$$\int mr \text{ ber } mrdmr = mr \text{ bei}' \, mr$$

and

$$\int mr \text{ bei } mrdmr = -mr \text{ ber}' \, mr$$

Dividing the voltage by I_1 and noting that $m^2 = \frac{4\pi\omega}{\rho_1}$,

$$Z_{eff} = R_{abs} + \frac{2\pi N^2\rho_1 ma}{l}\frac{\text{ber}' \, ma + j \text{ bei}' \, ma}{\text{ber } ma + j \text{ bei } ma} + j\frac{\omega 4\pi^2 N^2}{l}(b^2 - a^2) \text{ abohms} \qquad (8)$$

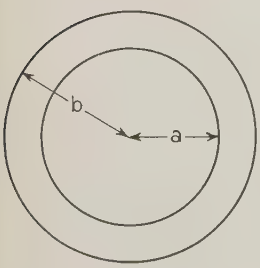


Fig. 1. Cross section of a coreless induction furnace

a = outside radius of charge
b = radius of primary coil

Rationalizing the denominator, and letting R = the a-c resistance of the primary coil in ohms and ρ = the resistivity of the charge in ohms per centimeter cube,

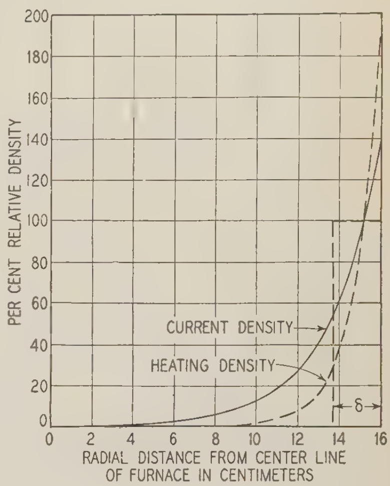
$$R_{eff} = R + \frac{2\pi N^2\rho ma}{l}\frac{\text{ber } ma \text{ ber}' \, ma + \text{bei } ma \text{ bei}' \, ma}{\text{ber}^2 \, ma + \text{bei}^2 \, ma} \text{ ohms} \qquad (9)$$

$$X_{eff} = \frac{2\pi N^2\rho ma}{l}\frac{\text{ber } ma \text{ bei}' \, ma - \text{bei } ma \text{ ber}' \, ma}{\text{ber}^2 \, ma + \text{bei}^2 \, ma} + \frac{8\pi^3 fN^2}{l}(b^2 - a^2)10^{-9} \text{ ohms} \qquad (10)$$

These are in agreement with the expression following equation 37, page 31, of reference 1 (see list at end of paper). Heaviside determined the magnetic field in the metallic core of a solenoid in terms of Bessel functions.[2]

Fig. 2. Relative current and heating densities in a typical coreless induction furnace

Diameter of furnace = 32 centimeters = 12.6 inches
Resistivity of charge = 200 × 10^{-6} ohms per centimeter cube
Frequency = 960 cycles per second
ma = 10
δ = 2.3 cm.



The series for the fractions in Bessel functions in equations 9 and 10 have been published,[3,4] and when they are substituted the following are obtained:

When ma is less than 2,

$$R_{eff} = R + \frac{2\pi N^2\rho}{l}\left(\frac{1}{2}ma\right)^4\left[1 - \frac{11}{24}\left(\frac{1}{2}ma\right)^4 + \frac{473}{2160}\left(\frac{1}{2}ma\right)^8 - \ldots\right] \text{ ohms} \qquad (11)$$

$$X_{eff} = \frac{4\pi N^2\rho}{l}\left(\frac{1}{2}ma\right)^2\left[1 - \frac{1}{3}\left(\frac{1}{2}ma\right)^4 + \frac{19}{120}\left(\frac{1}{2}ma\right)^8 - \ldots\right] + \frac{8\pi^3 fN^2}{l}(b^2 - a^2)10^{-9} \text{ ohms} \qquad (12)$$

When ma is greater than about 4, for slide-rule accuracy,

$$R_{eff} = R + \frac{\pi N^2\rho ma\sqrt{2}}{l}\left[1 - \frac{1}{ma\sqrt{2}} - \frac{1}{8m^2a^2} + \frac{25}{128m^4a^4} + \ldots\right] \text{ ohms} \qquad (13)$$

$$X_{eff} = \frac{\pi N^2\rho ma\sqrt{2}}{l}\left[1 + \frac{1}{8m^2a^2} + \frac{1}{4\sqrt{2}m^3a^3} + \frac{25}{128m^4a^4} - \ldots\right] + \frac{8\pi^3 fN^2}{l}(b^2 - a^2)10^{-9} \text{ ohms} \qquad (14)$$

When ma is between 2 and 4, values of the functions of the "ber" type should be taken from tables and used in equations 9 and 10. These tables have been published elsewhere.[5,6,7]

Note that

$$ma = 2\pi a\sqrt{\left(\frac{2f}{\rho \times 10^9}\right)} \qquad (15)$$

where a is the radius of the charge in centimeters and ρ is in ohms per centimeter cube.

An accurate experimental check on the first term of equation 14 has been made.[8] Sufficiently high frequencies were used so that terms in $1/m^2a^2$ and higher powers were negligible. Rods of copper and of alloys were used inside the primary coil. The resistivity of these cores was measured precisely with direct current, and the reactance at different frequencies was measured with alternating current. The agreement between measured and computed values was very close.

The current density at radius r in the charge is given by equations 2, 5, and 6, and is

$$i = \frac{1}{4\pi}\frac{d}{dr}\left[\frac{4\pi NI_1}{l}\,\frac{\text{ber } mr + j \text{ bei } mr}{\text{ber } ma + j \text{ bei } ma}\right]$$

$$= \frac{NI_1 m}{l}\,\frac{\text{ber}' \, mr + j \text{ bei}' \, mr}{\text{ber } ma + j \text{ bei } ma} \qquad (16)$$

$$= \frac{NI_1 m}{l}\,\frac{\text{ber } ma \text{ ber}' \, mr + \text{bei } ma \text{ bei}' \, mr + j(\text{ber } ma \text{ bei}' \, mr - \text{bei } ma \text{ ber}' \, mr}{\text{ber}^2 \, ma + \text{bei}^2 \, ma} \text{ abamperes per square centimeter} \qquad (17)$$

For computing numerical values, the tables of functions of the "ber" type may be used. If I_1 is in amperes, then i will be also.

Penetration Formula

The first 2 terms of the series in equation 13 for the effective resistance of the charge can be represented by assuming that the charge is replaced by its outermost shell of thickness

$$\delta = \frac{\sqrt{2}}{m} = \frac{1}{2\pi}\sqrt{\left(\frac{\rho \times 10^9}{f}\right)} = 5030\sqrt{(\rho/f)} \text{ centimeters} \qquad (18)$$

where ρ is in ohms per centimeter cube, and by assuming that the current density is uniform throughout the shell. The effective resistance of the secondary then can be computed by the following:

$$R_{eff} = \frac{\rho 2\pi(a - \delta/2)}{\delta l} \text{ ohms} \qquad (19)$$

referred to the secondary.

Substituting $\delta = \dfrac{\sqrt{2}}{m}$ in equation 19 and multiplying by N^2 for resistance referred to the primary, the first 2 terms of the second part of equation 13 are obtained. This gives the resistance with slide-rule accuracy for $ma = 6$ or larger. It is necessary to use $2\pi(a - \delta/2)$ for the perimeter of the shell and not $2\pi a$, or an error as large as 12 per cent will be made when $ma = 6$.

The reactance is not computed by means of the shell of thickness δ, but by the Bessel function calculation; however, it can be expressed in terms of δ, for $ma = 6$ or larger, directly from equation 14, as follows:

$$X_{eff} = \frac{2\pi a\rho N^2}{\delta l} + \frac{8\pi^3 f N^2}{l}(b^2 - a^2)10^{-9} \text{ ohms} \qquad (20)$$

The first part of this is not quite equal to the secondary resistance, but is 12 per cent larger when $ma = 6$, and 7 per cent larger when $ma = 10$.

Even where the frequency is high enough for the penetration formula to give the effective resistance with desired accuracy, the coreless induction furnace is not in every way equivalent to a primary coil and a shell of thickness δ. For instance, to assume such a complete equivalence and calculate flux density and exciting current by usual transformer formulas does not seem as safe as to compute these features by the fundamental equations given in this paper. A penetration formula derived for flat plates is not always suitable for cylinders.

The penetration formula is used also in calculations of conductors carrying high frequency current. It is a very useful device and is practically indispensable with irregular cross sections, so long as δ is considerably less than the radius of curvature of any part of the surface and so long as the frequency is sufficiently high. The limited extent of the equivalence of the shell of thickness δ to the actual body of metal, however, should always be kept in mind.

In figure 2 are shown the relative current densities and heating densities at different radii of a sample induction furnace in which $ma = 10$. The density if all the current were uniformly distributed in a shell of thickness δ is taken as 100 per cent.

Example

The following example illustrates the calculations for a typical furnace by the series and by the penetration formula:

Find the electrical characteristics of the following coreless induction furnace:
Average diameter of charge, $2a = 18$ inches
Length of charge, $l = 24$ inches
Resistivity of molten iron charge, $\rho = 200 \times 10^{-6}$ ohms per centimeter cube
Permeability of charge, $\mu = 1$
Diameter of coil, $2b = 25$ inches
Number of turns in coil, $N = 12$
Frequency, 960 cycles per second
Resistance of coil for 960 cycle current, 0.0030 ohms

$$ma = 2\pi \times 9 \times 2.54\sqrt{\left(\frac{1920}{200{,}000}\right)} = 14.1, \text{ by equation 15}$$

$$R_{eff} = 0.0030 + \frac{\pi \times 144 \times 200 \times 10^{-6} \times 14.1 \times \sqrt{2}}{24 \times 2.54}\left[1 - \frac{1}{14.1\sqrt{2}} - \ldots\right]$$

The series in square brackets = 1 − 0.05 = 0.95

$R_{eff} = 0.0030 + 0.0281 = 0.0311$ ohms, by equation 13

From this can be computed the first term of X_{eff}, which is

$$\frac{0.0281}{0.95} = 0.0296 \text{ ohms}$$

$$X_{eff} = 0.0296 + \frac{8\pi^3 \times 960 \times 144 \times 3.5 \times 21.5 \times 6.45 \times 10^{-9}}{24 \times 2.54}$$

putting $b^2 - a^2 = (b - a)(b + a)$

$X_{eff} = 0.0296 + 0.273 = 0.303$ ohms, by equation 14

$Z_{eff} = \sqrt{(0.0311^2 + 0.303^2)} = 0.319$ ohms

$$\text{Power factor} = \frac{R_{eff}}{Z_{eff}} = \frac{0.0311}{0.319} = 0.098 \text{ or } 9.8 \text{ per cent}$$

$$\text{Efficiency} = \frac{R_2}{R_1 + R_2} = \frac{0.0281}{0.0311} = 0.90 \text{ or } 90 \text{ per cent}$$

By the penetration formula, equation 18,

$$\delta = \frac{1}{2\pi}\sqrt{\left(\frac{200{,}000}{960}\right)} = 2.30 \text{ centimeters}$$

Resistance of skin depth of charge, by equation 19

$$= R_{eff} = \frac{200 \times 10^{-6} \times 2\pi(9 \times 2.54 - 1.15) \times 144}{2.30 \times 24 \times 2.54}$$

$$= 0.0281 \text{ ohms, referred to the primary side.}$$

It should be noted that all the dimensions in the formulas are in centimeters.

References

1. Theory of Eddy-Current Heating, C. R. Burch and N. R. Davis. E. Benn, Ltd., London, 1928.

2. Heaviside's Electrical Papers, The Copley Publishers, Boston, Mass., v. 1, p. 360; or *The Electrician*, May 3, 1884, p. 585.

3. Theory of Alternating Currents, A. Russell. Cambridge Univ. Press, 1914, v. 1, p. 211, eqs 29, 30, 35, and 36.

4. The Calculation of Mathematical Tables, Part IV, H. G. Savidge. Report of British Assn., 1916, p. 114–5.

5. Reports of the British Association for the Advancement of Science, 1912 and 1916.

6. Bessel Functions for A-C Problems, H. B. Dwight. A.I.E.E. Trans., v. 48, 1929, p. 812.

7. Tables of Integrals and Other Mathematical Data, H. B. Dwight. The Macmillan Co., N. Y., 1934, p. 211.

8. Measurement of Specific Resistance by Eddy Current Shielding, W. B. Kouwenhoven and G. P. Daiger. *Rev. of Sci. Instruments*, v. 5, Feb. 1934, p. 94.

Sparking Under Brushes of Commutator Machines

Sparking under the brushes of commutating machinery has been investigated in considerable detail, for the purpose of studying and analyzing the various factors which cause sparking. Among the conclusions reached are that in a detailed consideration of sparking phenomena both current density and rate of change of current density must be taken into account.

By
R. E. HELLMUND
FELLOW A.I.E.E.

L. R. LUDWIG
ASSOCIATE A.I.E.E.

Both of the Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

DURING the time interval when any armature coil of a commutator machine is short-circuited by the brush, the current in the coil must be reversed. If it is completely reversed to the exact value of the normal current in the armature coil as the commutator bar leaves the brush, no current has to be interrupted and, consequently, no sparks will be formed at the trailing edge of the brush. Even greater assurance of sparkless operation at the trailing edge can be obtained if the current reversal is accomplished slightly before the segment leaves the brush and if no voltage is induced in the coil for the remainder of the commutating period. At the leading edge of the brush, no sparking is to be expected if no voltage is induced in the coil at the time it is short-circuited.

The trailing-edge type of sparking, when it does occur, is always due to the interruption of a current—that is, to a switching phenomenon. If sparking at the leading edge occurs, it is due to the presence of a voltage induced in the coil as it is short-circuited. The current which passes through the minute points of initial contact at the brush edge in consequence of this voltage is likely to heat the contact points sufficiently to cause sparking. The phenomena at the edges of the brush and various factors affecting them have been dealt with in a previous paper by the authors.[1] In the same paper it was shown that in d-c machines the ideal conditions at the edges, as briefly described in the previous statements, are associated with a flat initial and final portion of the time curve. From these considerations alone, it appeared to be of no consequence how the coil current changes as a function of time during the period between the small initial and final part of the curve.

There is, however, a third type of sparking, namely, that under the brush, which can be observed in quite a number of machines and with regard to which the intermediate course of the current curve may be of importance. It is the purpose of this paper to present the results of experiments which indicate the physical causes of sparking under the brush and to review the factors in design which affect them.

The Basis for Investigation of Sparking Under a Brush

An obvious physical cause for sparking under a brush is the effect of mechanical roughness, which in severe cases might result in complete, though momentary, separation of the brush from the commutator. Although this undoubtedly can be and

A paper recommended for publication by the A.I.E.E. committee on electrical machinery, and tentatively scheduled for discussion at the A.I.E.E. summer convention, Ithaca, N. Y., June 24–28, 1935. Manuscript submitted Sept. 25, 1934; released for publication Nov. 13, 1934.

1. For all numbered references, see list at end of paper.

frequently is a cause of sparking under brushes, such sparking can at times be observed even with a high degree of mechanical smoothness, and one is forced to doubt that mechanical roughness is its sole possible cause. High local current densities have frequently been suggested as another likely cause of sparking under brushes. However, certain experiments showing sparkless operation with densities much in excess of those occurring under brushes of machines, indicated that high densities in themselves would not satisfactorily explain all cases of sparking under the brush. Therefore, a further study of the electrical nature of the contact between the brush and a commutator or ring is needed in order to arrive at an explanation of the phenomenon.

A sliding brush contact exhibits the peculiar characteristic that as its current increases its resistance decreases. In figure 1, curve *a*, a static volt-ampere characteristic of such a contact has been plotted. The data for the curve were obtained with a graphite brush (0.1 square inch in area) on a brass ring. The ring was 5 inches in diameter, and was run at 1,200 rpm. The brush was $^3/_{16}$ x $^9/_{16}$ inch, and the spring pressure on it was 15 pounds. Direct current entered the brush, passed to the ring, and was then conducted to a second ring on the same shaft and out through another brush. A third ring on the shaft was also connected to the other 2, and a copper brush was placed in contact with this ring. The contact drop of the tested brush was measured by connecting a voltmeter between this brush and the copper brush. A separate test showed the contact drop of the copper brush, when carrying sufficient current to operate the voltmeter, to be less than 0.05 volt, which is a negligible value. Several minutes elapsed at each current setting before the voltage was read. (In all of the curves in the paper the ohmic drop of the brush itself has been subtracted from the voltage readings.)

The variable contact resistance shown by curve *a* in figure 1 was, of course, obtained under "steady state" conditions. If the current density in the contact was allowed to change rapidly, an entirely different characteristic was obtained. The transient characteristics of the contact were therefore investigated in the hope of finding an explanation of the sparking under a brush.

The Nature of Dynamic Contact Volt-Ampere Characteristics

An experiment to determine the dynamic contact characteristics was made, again using the apparatus described and with the circuit shown in figure 2. The availability of electronic devices made it possible to establish testing conditions that could not be readily obtained during many of the earlier investigations of contact phenomena. As a consequence, some very interesting results were obtained. A rectifier of the type utilizing an ignitor rod in contact with the mercury to control the starting of the arc was connected in series with the brushes, and during each positive half-cycle the starting of this rectifier was delayed until some time after the voltage had reached its maximum value. In this way, an extremely

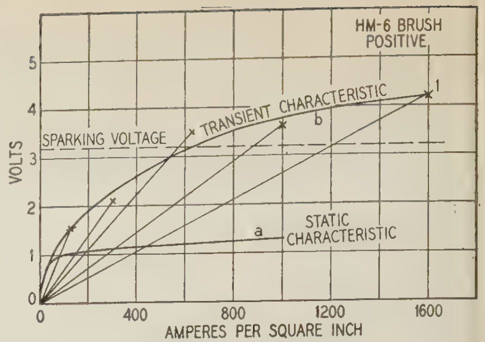


Fig. 1. Brush volt-ampere characteristics

a. Static
b. Rapidly increased current

rapidly rising current through the brush was obtained. An oscillogram of the current in the brush and the contact drop of the brush is reproduced in figure 3. A number of such oscillograms were taken, and in each a different peak value of current was obtained by changing the series resistance as each film was recorded. The peak value of current and the peak value of voltage were then obtained from each of the films, and in figure 1, a curve *b* has been plotted using these points. Therefore, the curve represents the voltage obtained with a rapidly increasing current. It will be noted that this curve lies considerably above the static curve, though it has a somewhat similar shape.

Conditions for Sparking Under a Brush

Some of the points on curve *b* represent contact voltages which are several times normal. Sparking under the brush was observed as these points were being obtained. This was the case while the film reproduced in figure 3, for example, was being recorded. The maximum value of the current shown on the film is 160 amperes, corresponding to a current density of 1,600 amperes per square inch. With this same current flowing through the brush continuously no sparking was observed, and as can be seen from figure 1 the contact drop in the case of the continuous current was very much less. These 2 tests were made a few minutes apart and the mechanical conditions were practically identical.

The sparks observed apparently were due to either the production of small incandescent particles, or to the formation of a gaseous discharge, as a result of the abnormal contact voltages. Slepian[2] has shown that a potential of a few volts, when impressed across a diminishing contact area of a material similar to that from which brushes are made, will heat the separating points to a few thousand degrees. Thus a virtual "explosion" of small particles of carbon under the brush might produce the luminous sparks. On the other hand, if the contact voltage becomes sufficient, sparks having the character of a low current arc might be formed and momentarily maintained. Small arcs could be formed easily, due either to the breaking of local points of contact under the brush as the ring revolves, or to the high potential gradient across a local contact point with such local contacts acting as small "ignitor electrodes."[3]

The question then arises as to the value of the voltage which will cause sparking underneath the

brush. A test was made by first using such values of current that sparking was observed, and then by decreasing this current until the sparking just vanished. From the oscillograms it was found that for this particular brush, a value of 3.2 volts was typical of the potential at which sparking began to be noticeable. Referring again to figure 1, it will be seen that at the higher currents the voltages given by the upper curves are considerably in excess of this value, and sparking was continuously observed when all of these points were being obtained. A horizontal line designating the sparking voltage has also been drawn in the figure.

The volt-ampere characteristics in figure 1 will, of course, be expected to vary from one kind of brush to another. Several brushes have been tested in the same way, and with a given current the actual values of voltage do vary. However, for all of the carbon grades tested so far, sparking occurred at about the same value, namely, approximately 3.2 volts.

Effect of the Rate of Current Increase on the Contact Voltage

Instead of increasing the current very rapidly through the brush contact, an experiment was made by using a sinusoidal current-wave of 60 cycle frequency. The brush was cold prior to the initiation of current, and it was positive with respect to the ring during the first half-cycle of current flow.

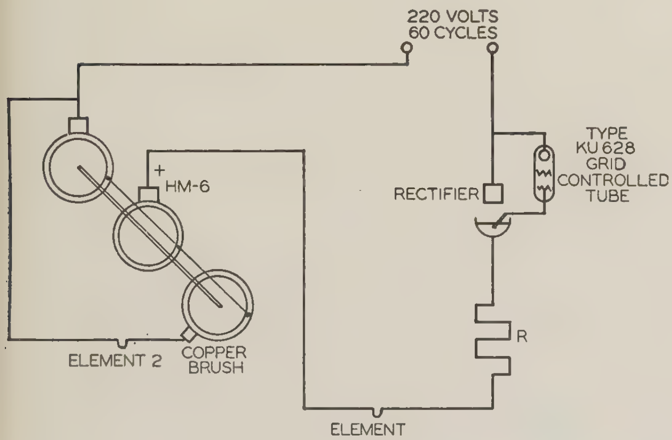


Fig. 2. Testing circuit

A volt-ampere characteristic obtained from this first half-cycle of conduction is plotted in figure 4, curve A. The static curve from figure 1 has been reproduced in figure 4 for reference. Although the 60 cycle curve lies above the static curve, the sinusoidal rate of current increase was not sufficient to produce contact voltages high enough for sparking, with a reasonable current.

After 2 cycles of operation the character of the 60 cycle dynamic curve changed, and in figure 4 a second curve B has been plotted showing its form. A half-cycle was plotted during which the brush was positive. The contact resistance, according to this curve, is almost constant and the contact voltage for any current is less than that obtained during the first half-cycle of conduction as shown by curve A.

As time progressed, a further change took place in the 60 cycle curve. The entire curve fell, and its final form is shown in curve C, figure 4. Several seconds must elapse before the curve changes from the form B in figure 4 to that of C in the same figure. The brush was positive during the half-cycle from which this curve was plotted also.

Theory of the Dynamic Characteristics

In curve C, figure 4, the a-c resistance of the contact is seen to be substantially constant. At the point where the static characteristic intersects the 60 cycle curve C, the d-c resistance of the contact is, of course, equal to the constant a-c resistance. This point will be seen to correspond closely to the root mean square value of the a-c current; that is, the contact has the same resistance when the direct current and the root mean square alternating currents are equal and when "steady state" conditions have been reached. This fact strongly suggests that the contact resistance is a function of the temperature at the contact region. Thirty-two years ago, Kahn[4] found similar results. Slepian,[2] and later Ludwig and Baker[5] made the same suggestion from other data. Holm[6] has found the contact temperature to be of fundamental importance in explaining the action of stationary contacts. Explanation of the mechanism by which the contact temperature produces the observed variation in contact resistance, have been varied and dissimilar, however. Without attempting to be explicit as to mechanism, it is of interest to discuss the curves that have been presented on the basis of a thermal cause for the variations of contact resistance.

In figure 4 the difference between curves A and B could be due to the thermal time lag of the contact; that is, about 2 cycles are required before the temperature at the contact might increase sufficiently to cause a generally decreased resistance. Of course, curve A itself exhibits the phenomenon of a resistance which is variable with current, but this is to be expected because a cold brush will probably have very small contact regions, which will consequently be heated and cooled very rapidly. In 2 cycles a larger amount of material would be heated, and the number as well as the size of the contact regions may

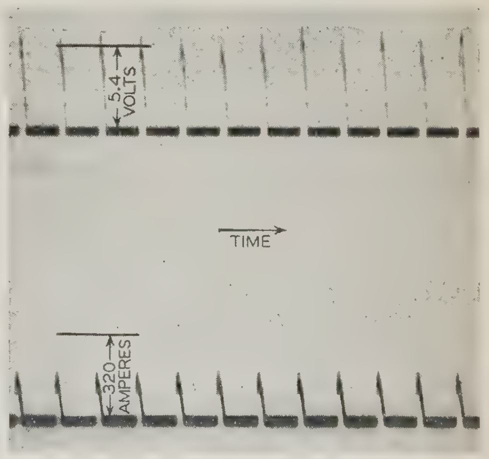


Fig. 3. Oscillogram showing the effect of a rapidly increased current through a brush contact

be considerably increased. As the regions become larger, they will heat and cool more slowly, and curve B shows that the resistance no longer changes appreciably as the current varies, as well as the fact that the mean value of the resistance has decreased from the original value associated with curve A.

Curve b in figure 1 is really the envelope of a number of curves, one for each point through which b was drawn. These individual curves can be drawn only by using one point and the origin, because the rapidity with which the current rises precludes the measurement of intermediate values. However, since the oscillograms from which these points were obtained were made under conditions similar to that from which curve B, figure 4, was taken except that the current was increased more rapidly, probably the individual curves are also nearly linear. They have been drawn as linear in figure 1, and when plotted they give the appearance of rays extending from the origin to the points on curve b. The entire curve b is thus seen to be similar to the rising branch of curve A in figure 4. Curve b is actually higher than curve A because of the greater rapidity of current increase, and it becomes evident that if the current in a cold brush were rapidly increased from zero to point 1 on curve b in figure 1, the voltampere characteristic would be similar to curve b, but it might be higher because the peak value of voltage is not reached after the first cycle, and curve b is not the initial curve corresponding exactly to A in figure 1. The fall of contact resistance with increased current which is shown by curve b may again be ascribed to the increase in temperature of the contact region with the current. The contact voltages represented by curve b are considerably greater than those represented by curve A in figure 4, however, presumably because the contact temperature will follow the current less closely in time as the rate of current rise is increased. In other words, the high contact voltages associated with a rapidly increased current are the result of the thermal time lag of the contact. After the lapse of a cycle or so of current through the brush, having the wave form shown in figure 3, the volt-ampere characteristic would be represented closely by the line drawn from the origin to point 1 on this curve. The contact voltage given by this point is maintained for some time, as shown by the oscillogram in figure 3, because of the wave form of the current. That is, its peak value is $3^1/_2$ times the root mean square value, and if the resistance remains substantially constant and is determined by the root mean square current (as is true with the 60 cycle curves), then the peaked current wave should repeatedly cause abnormal contact voltages.

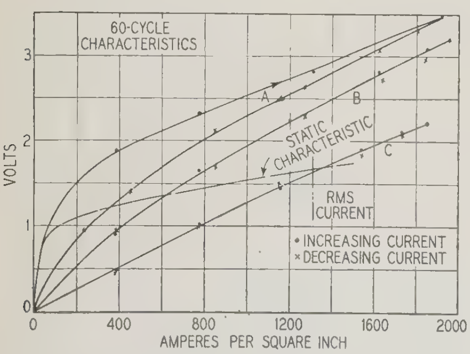


Fig. 4. Brush volt-ampere characteristics on 60 cycles

A. Initial half cycle
B. After 2 cycles
C. After 5 minutes

In figure 4, the difference between curves B and C may also involve the temperature. Another explanation would be to associate this slow change with the "polishing action" of the current on the contact. Thus, it is known that the passage of current through a contact will reduce the brush friction, probably because of an electrical transfer of material which aids the polishing action. This "smoothing" of the brush surface would be expected to establish more intimate contact with the ring and thus lower the contact drop. This suggestion is supported by the observation of the comparatively long time required for the transition from curve B to curve C. It is further supported by unpublished results obtained by the late G. M. Little, which showed that if direct current was suddenly passed through a brush contact, the voltage-time curve would fall rapidly just after its initial value had been reached, and then, after a sharp break in the slope of the curve, a very slow decrease would ensue. After the oscillogram in figure 3 was taken, sparking under the brush seemed to increase in intensity with time. This fact at first seems contrary to what would be expected from the curves B and C in figure 4, since they indicate a reduced contact voltage as time passes. It must be realized, however, that with abnormal voltages across the contact, brush polish will be quickly destroyed; in fact, if sparking under a brush persists, the face is soon badly eroded, the ring blackened, and the contact voltage is actually observed to increase.

Thus, thermal changes alone do not seem to explain fully the electrical nature of the sliding contact, although they appear to have a basic influence and to be consistent with the observations. In addition to this effect and the "polishing" action just described, the authors are inclined to believe that with sliding contacts the phenomenon is appreciably influenced by partly or entirely loose particles coming from the brush, as outlined by Hellmund.[7] There is little doubt that under many, if not all, operating conditions, the segments or portions of rings when leaving the brush carry with them loose particles from the brush in a certain temperature condition. These particles will naturally cool off to a certain extent before they are carried back under the brush. When entering, they create certain resistance conditions both on account of their temperature and of mechanical influences on the relation of the brush and carbon surface. As soon as they take part in carrying currents, they heat up and possibly are burned away, thus again causing changes in the contact condition. At the same time, new particles may tear loose from the carbon surface, bringing about further changed conditions. It is believed that phenomena of this kind may be an especially important factor under severe operating conditions. It is also believed that this phenomenon of partly or entirely loose particles varies appreci-

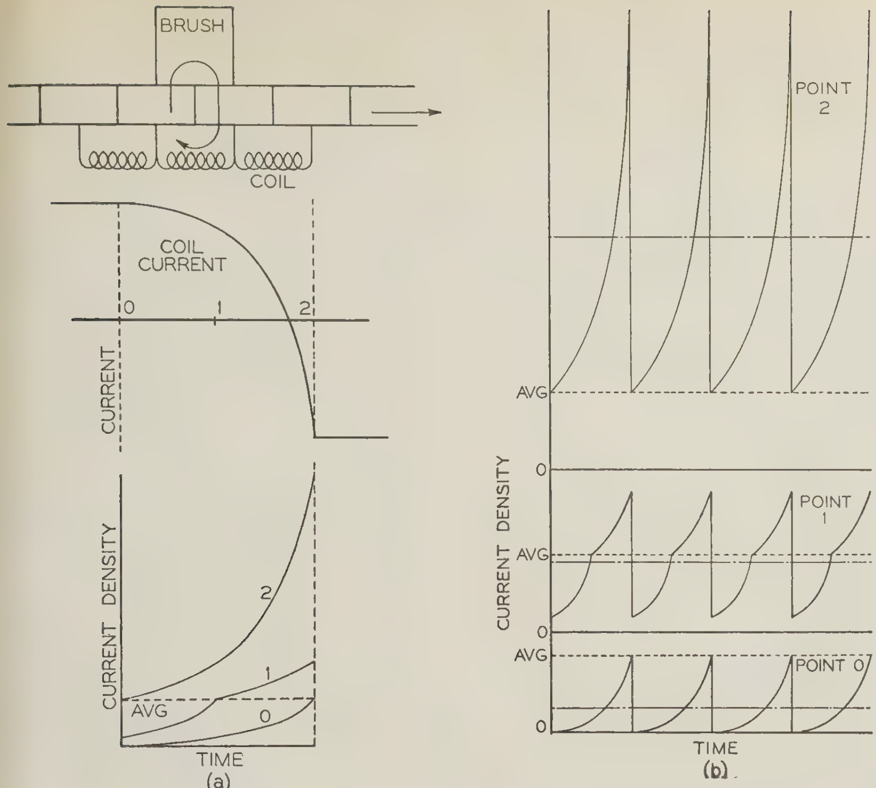


Fig. 5. A typical commutating condition for a generator (a, left); and current densities at 3 points under the brush (b, middle)

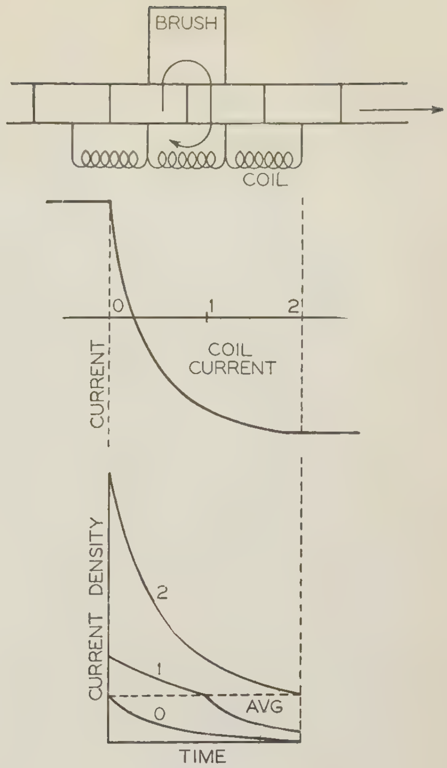


Fig. 6. A typical commutating condition for a motor

ably with the mechanical structure of the carbon used and that it may be an explanation for much of the difference in the practical performance of different grades of carbons.

So far it has been assumed that the particles are conducting; in addition it should, however, be appreciated that on account of frequently existing impurities in carbons some of the loose particles may be insulators, which may have further and quite appreciable influence upon the contact and arcing phenomena and may further explain certain differences observed in practice. Although a complete theory with regard to all these factors cannot be outlined at this time and is not essential in connection with this study, these various possibilities have been briefly mentioned in order to show that aside from the effective current densities in the contact surface, many other factors, such as the mechanical structure of the brushes, their chemical composition, the time during which the various ring or commutator portions are under the brush and between brushes, the temperature and current conditions at the instant of the test as well as the temperature and current condition preceding, are likely to have a marked influence upon the resistance and sparking conditions under the contact surface.

These suggestions are quite consistent with the theories advanced by several authors that a film of copper oxide between the brush and the ring may play a dominating part in the conduction phenomenon. In fact, the combination of such a film and "loose particles" seems to make possible a satisfactory explanation of most of the observed phenomena.

However, regardless of the practical importance of the various factors mentioned, the investigations made definitely indicate that a rapidly increased current through a brush contact will generate, at least momentarily, a contact voltage considerably in excess of that obtained if the same current passes though the brush continuously. It is also evident from the curves that repeating peaked current wave will cause abnormal contact voltages. Therefore, the transient voltage across the contact must be considered as depending upon the rate of rise of the current and the ratio of the peak to the root mean square value if the phenomenon is a repeating one. It has also been found that if this contact voltage exceeds a value of about 3.2 volts, sparking under the brush will occur. With these data obtained from the tests described, a review of some of the design features of commutator machinery will be made for the purpose of determining the desirable path in time of the current reversal in a short-circuited coil. The criterion for determining the most suitable path is that the current density in any portion of the brush must not reach excessive values and that it must not increase too rapidly.

Typical Conditions of Commutation

It is well known that in straight-line commutation the current is always equally distributed under the brush both in space and in time. It is therefore evident that with this type of commutation, ideal conditions under the brush are obtained because any densities in excess of the average are avoided and sudden changes in density are entirely elimi-

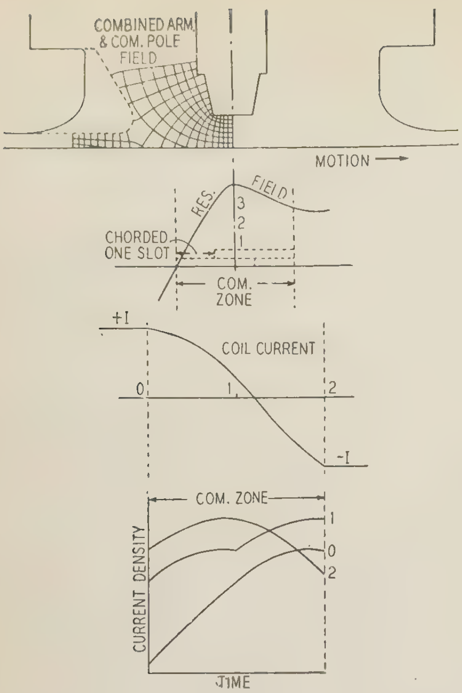


Fig. 7. A desirable commutating condition

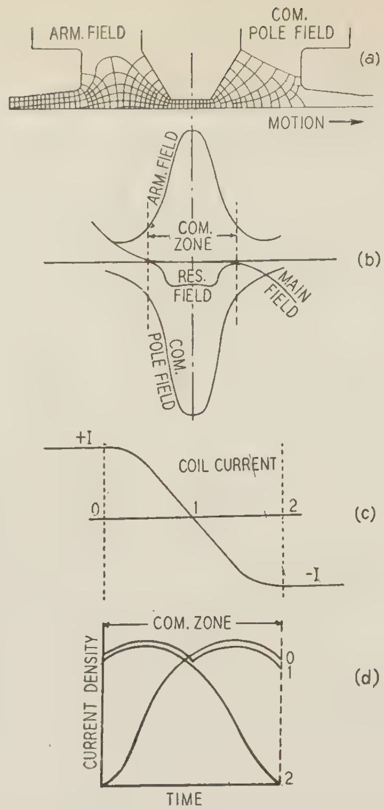


Fig. 8. An "ideal" condition of commutation practically realized

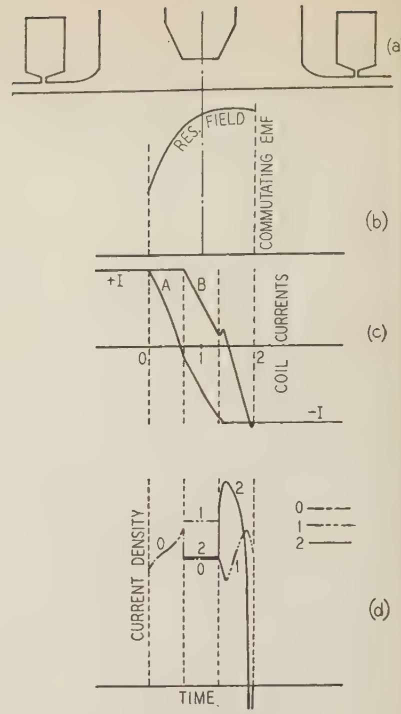


Fig. 9. Commutating condition with multiple coils per slot

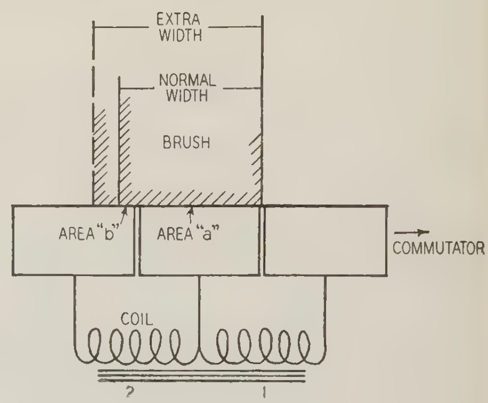


Fig. 10. Effect of multiple coils per slot at the entering brush edge

nated. However, as is also well known, straight-line commutation is difficult to obtain in actual practice.

Figure 5 shows a rather common condition of commutation in which the current is completely reversed in the available time but with most of the reversal occurring during the latter part of the commutating period. This is a condition commonly found in generator operation. One coil per slot and one bar per brush were assumed in drawing the figure.

Figure 5 also shows the variation of current density and time for 3 different points (0, 1, and 2) under the brush, and figure 5*b* shows these curves repeated for the same points, namely, the leading edge, center, and trailing edge of the brush. It will be noted that near the trailing edge the current densities are 5 to 6 times as high as the average density. Even at a point removed about $^1/_5$ from the trailing edge, densities as high as 3 times the average are obtained. It is therefore evident that in the case of overload and high average current density, a density greatly in excess of the average at the trailing edge together with a rapid change in density may lead to sparking under the brush. Assuming an average density of 100 amperes per square inch and conditions obtained from tests as indicated in curve *b* of figure 1, voltages near the trailing edge just high enough for sparking might occur.

Figure 6 shows a related condition which may occur in the case of motor operation with similar field conditions, and it is at once evident that in this case sparking may occur near the leading edge of the brush.

In figure 7, field conditions have been developed with the idea of obtaining as favorable proportions as are practicable in larger machines with relatively large interpole gaps. It will be noted that sudden rises in density as well as densities much in excess of the average have been avoided, and therefore good commutating conditions are to be expected. This latter condition has been obtained with the aid of some chording in the armature.

The ideal form for the curve of coil current and time with reference to the operation at the edges of the brush suggested by the authors in a previous paper, is shown in figure 8. These conditions frequently can be approached in practice in smaller machines with relatively small commutating pole air gaps and pointed commutating poles. From figures 8*c* and 8*d* it will be noted, however, that although no densities much in excess of the average are obtained, there are fairly sudden changes in current density, but from the test data obtained,

this is not likely to lead to sparking under the brush unless excessively high average densities are also present.

Figure 9 illustrates a typical case of a large machine with 2 commutator bars under the brush and 2 coils per slot. With the large air gaps of commutating poles commonly used, the commutating field is unsymmetrical, as shown in figure 9*b*, and as a result it is impossible to obtain conditions in which commutation is completed in both of the coils when they leave the brush. The best compromise that can be obtained is in having one of the coils under-compensated and the other one over-compensated, as indicated in figure 9*c*. Current densities corresponding to such a condition are shown in figure 9*d*, and here it becomes quite evident that there are not only high densities but also very sudden increases in density, which undoubtedly invites sparking under the brush near the trailing edge. These conditions may also appreciably affect sparking under the brush. The sudden interruption of the current in one coil as it leaves the brush will on account of the mutual induction necessitate a sudden change of current in the adjacent coil of the same slot, and consequently sudden and extreme density variations in certain portions of the brush will lead to sparking under it. A case of this kind is illustrated in figure 10. It may be assumed that a short-circuit current is suddenly interrupted in coil 1 in the position shown. An almost equal current must suddenly appear in coil 2, which will cause a sudden change of current in both portions *a* and *b* of the brush. In portion *a* the density may not be very high and therefore the sudden change may not be of practical importance, but in *b* a combined high density and sudden change in current will probably cause sparking. It is thus evident that the various factors discussed in the previous paper which are favorable toward the avoidance of sparking at the edge of the brush will for the same reasons assist in minimizing sparking under the brush. It is interesting to note that if in an a-c motor, for instance, the brush were made wider, thus reducing the current density in portion *a*, it might have a favorable effect, although a narrow brush-span in a-c motors is usually considered favorable. It has actually been found in practice that under such conditions a somewhat wider brush in a-c motors showed improvement, though this is not generally nor always the case because so many factors enter into it.

Summary

In previous discussions of commutating ph nomena, it has been appreciated that many of the difficulties encountered were due to the fact that under certain portions of the brush the densities became higher than the average. However, it has been found by tests that with a constant high density no sparking is obtained on a slip ring even with densities appreciably in excess of the values commonly used in commutator work. For example, some of the tests recorded here indicate that under static conditions no sparking is obtained for densities of 1,000 amperes per square inch; however it has been found that with a combination of high densities and sudden changes in density sparking is obtained at considerably lower values of density. Consideration of the various commutating conditions in this paper indicates that it is probably this combination which results in sparking under the brush. The natural conclusion therefore is that in a detailed consideration of these phenomena both factors must be taken into account.

References

1. Commutation Considered as a Switching Phenomenon, R. E. Hellmund and L. R. Ludwig. A.I.E.E. Trans., v. 51, 1932, p. 465–8.

2. Temperature of a Contact, Joseph Slepian. A.I.E.E. Jl., v. 45, Oct. 1926, p. 930–2.

3. A New Method for Initiating the Cathode of an Arc, Joseph Slepian and L. R. Ludwig. A.I.E.E. Trans., v. 52, 1933, p. 693–8.

4. Der Ubergangswiderstand von Kohlenbursten, Max. Kahn. *Sammlung Elekt. Vort.*, 1902, p. 435–91.

5. Influence on Commutation of Brush Contact Drop, L. R. Ludwig and R. M. Baker. A.I.E.E. Trans., v. 51, 1932, p. 959–63.

6. Uber Metallische Kontaktwiderstande, R. Holm. *Wiss. Veroff aus dem Siemens Konzern*, v. 7, pt. 2, 1929, p. 435–91.

7. Discussion of Reference Number 5, R. E. Hellmund. A.I.E.E. Trans. v. 51, 1932, p. 963–4.

A view of Cornell University, Ithaca, N. Y., scene of the A.I.E.E. 1935 summer convention to be held June 24–28

Discussions

Of A.I.E.E. Papers—as Recommended for Publication by Technical Committees

On this and the following 13 pages appear the first discussions submitted for publication and approved by the technical committees on papers presented at the sessions on cables and overhead line problems at the 1935 A.I.E.E. winter convention, New York, N. Y., January 22–25. Other discussions of these and other winter convention papers, and authors' closures, will be published in later issues.

Members anywhere are encouraged to submit written discussion of any paper published in ELECTRICAL ENGINEERING, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions on papers scheduled for presentation at an A.I.E.E. meeting or convention will be closed 2 weeks after presentation. Discussions should be: (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, A.I.E.E. headquarters, 33 West 39th Street, New York, N. Y.

Dielectric Properties of Cellulose Paper

Discussion of a paper by J. B. Whitehead and E. W. Greenfield published in the October 1934 issue, pages 1389–96, and in the November 1934 issue, pages 1498–1503, and presented for oral discussion at the cables session of the winter convention, New York, N. Y., January 24, 1935.

F. W. Godsey, Jr. (Sprague Specialties Co., North Adams, Mass.): This paper invites speculation as to the nature of the absorption losses reported for the cellulose paper investigated.

Kraft (or any other paper) is not pure cellulose. In addition to approximately 90 per cent alpha cellulose, there are present other celluloses such as oxycellulose with a much greater affinity for water than alpha cellulose. Resins, lignin, and similar substances are present as impurities in the paper facilitating the beating action and the formation of cellulose gel, which is essential to the felting properties of wood pulp fiber on the paper machines. These impurities exist in the finished paper as finite particles, along with a residue of chemical impurities resulting principally from pulp cooking processes.

With or without the presence of water, such an aggregate would exhibit dielectric absorption on the basis of the Maxwell-Wagner theory. Water in the paper will accentuate dielectric absorption due to the varying liquid absorption constants of the different materials present, and it is possible that relatively small amounts of water may cause relatively large changes in absorption.

It would have been interesting to note dielectric and power factor changes had the temperature experiments been carried well below the freezing point of water. Similarly, the sudden increases in absorption capacity and absorption loss reported in table IV at 99.3 degrees centigrade, just under the boiling point of water at atmospheric pressure, would have been interesting to follow through higher temperatures.

Dried glycerol-free cellophane has been investigated by W. N. Stoops (*Am. Chem. Soc. Journal*, volume 56, page 1480). This is practically pure cellulose, yet it shows absorption losses and capacity changes at frequencies between 60 cycles per second and one megacycle per second with frequency and temperature dependence of the sort found for ice and polar liquids of both low and high viscosity.

This cellophane is similar to paper capacity-frequency characteristics of the type shown in figure 4 of the paper at low frequencies. It decreases in capacity by very small amounts until 10 kilocycles are reached, but instead of flattening out as do the curves of figure 4, capacity continues to decrease until at one megacycle the capacity has fallen approximately 10 per cent with the trend still downward. It is quite likely that if the curves of figure 4 for dry paper are carried to still higher frequencies a similar decrease will be found and the true geometrical capacity will be less than the assumed value in computing moisture content.

Likewise, power factor of cellophane may increase with decreases in temperature; but if the frequency is carried high enough, power factor increases to maximum values between 100 kilocycles and one megacycle. At 60 cycles, the shape of the power factor-temperature curve of cellophane is quite similar to the curve for paper in figure 19. Not much information is given by Stoops as to the drying process used, and small quantities of free water may have been present.

Curves of d-c discharge in figure 5 are of a shape that indicates intricate Maxwell-Wagner dielectric or electromotive equilibrium processes. Probably both exist to appreciable extents.

Electromotive equilibrium or electrolytic polarization may exist in 3 different ways in liquid films or in the solid paper structure with solid ionization. Helmholtz double layers may exist at boundaries between dissimilar materials, and are independent of frequency with a very small phase displacement. Diffusion or concentration capacity is inversely proportional to the square root of the frequency, has a phase angle of 45 degrees leading, is inversely proportional to the absolute temperature, and is usually large enough to obscure double-layer effects. In the case of an ionogent so little dissociated and of such a concentration that a polarization on account of the change in concentration of the ionogent under weak currents is imperceptible, a polarization can occur, nevertheless, if the speed of dissociation of the nondissociated part of the ionogent does not ensue quickly enough compared to the current change to prevent a change in ionic concentration. In this case the capacity is inversely proportional to the frequency and the phase displacement is close to 90 degrees. This condition might arise in cases of solid ionization.

The variations of reversible absorption capacity and absorption loss with moisture content, temperature, and frequency as shown in tables I and IV, and figures 4 and 17 permit a few comparisons.

Absorption capacities scaled from the curves of figures 4 and 17 appear to be inversely proportional to frequency except at frequencies below 200 cycles per second as closely as the curves may be scaled. Below 200 cycles per second, absorption capacity increases much too rapidly with decreasing frequency to be fully accounted for by polarization capacity. Maxwell-Wagner phenomena can account for such changes, or possibly large micelles with very high dipole moments such as are suggested for pure cellulose.

Absorption losses referred to absorption capacities calculated from short time d-c discharge curves in table I vary from power factors of 0.60 at 0.25 millimeters drying pressure to 0.73 at 765 millimeters. Table IV, which does not agree with values in table I for the same paper, shows absorption power factors from 0.375 at 23.5 degrees centigrade to 0.495 at 99.3 degrees centigrade. Diffusion capacities, which have been shown to be insufficient to account for all of the absorption capacity at 60 cycles, have a power factor of 0.707.

Likewise, the rate of decrease of absorption capacity with increasing temperature is much too high to be explained upon the basis of diffusion capacity alone where capacity is inversely proportional to absolute temperature.

The free water content of paper as estimated by the authors is normally extremely

small. Assuming 10 microns as the average fiber diameter, if all of the water is evenly distributed in surface film, for 0.05 per cent water (0.25 millimeter drying pressure) the layers are approximately one molecule thick. For 0.26 per cent water (765 millimeters drying pressure) the estimated thickness is 8 molecule layers. The approach to a monomolecular film explains the great difficulty in reducing the water content below 0.05 per cent.

It is probable that considerable portions of the ordinary losses in cellulose papers must be assigned to 3 types of reversible absorption, Maxwell-Wagner layer dielectrics, polar rotation, and electrolytic polarization; and only under extreme conditions of frequency, temperature, etc., would it be possible to separate them.

Exception must be taken, however, to the statement, "Were it possible completely to remove all moisture, the paper would show no absorption, zero power factor, and 60 cycle capacitance equal to the geometrical capacitance." Aside from the questions of polar rotation in the cellulose, solid ionization, etc., zero power factor implies a completely reversible reaction which, of course, is unknown. The power factor may be much lower than any hitherto measured losses in dielectrics, although that does not necessarily follow from test results and figure 12.

H. H. Race (General Electric Co., Schenectady, N. Y.): In line with the data presented on the electrical properties of kraft paper during drying, I should like to present correlating data from actual cable manufacturing practice.

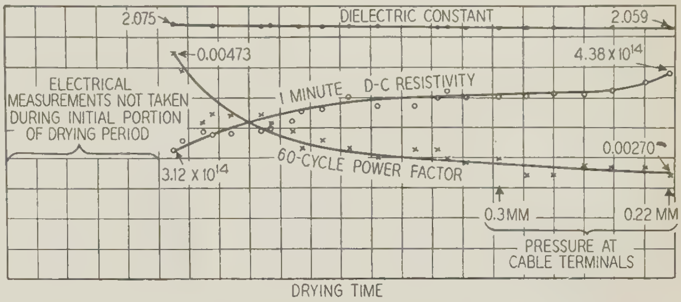
The data shown in figure 1 of this discussion were obtained on a full length of standard single conductor paper cable of the oil filled type. Moisture and air were removed through a central channel in the core by connecting the ends of the cable to vacuum pumps. The cable was held at a temperature of 100 degrees centigrade during drying. The length of the cable was of the order of 1,000 times the length of Whitehead's sample and the thickness of paper was about 10 times greater. Variations in points on the resistivity and power factor curves are probably caused by changes in temperature as a result of washing with carbon dioxide gas, rather than by errors in measurement. No time scale is indicated on the graph since the total drying time depends largely upon the length of the cable and the thickness of the insulation.

These curves demonstrate the very interesting and rather remarkable facts that in actual practice final vacuum pressure and final power factor values are obtained quite comparable to the values reported in figure 1 of the paper for a laboratory test.

No measurements were made during the first quarter of the drying period but during the last 3 quarters the effective dielectric constant decreased only about 1 per cent, while the power factor decreased 43 per cent and the effective one minute resistivity increased 40 per cent. All 3 of these electrical yardsticks are taken as routine measurements during the drying of all lengths of oil filled paper cable during manufacture, and oil is not admitted until these electrical control measurements reach predetermined values.

In figure 2 of this discussion is plotted a long time d-c current-time curve for this same length of cable taken at the end of the drying period and corresponding to the last point in figure 2. At the end of 10 minutes

Fig. 1. Electrical measurements taken on full length of high voltage paper cable during drying period at 100 degrees centigrade



the apparent conductivity had decreased to 5.6×10^{-16} mho per centimeter cube. If the test had been continued for 40 or 60 minutes as was done by Whitehead the apparent conductivity would probably

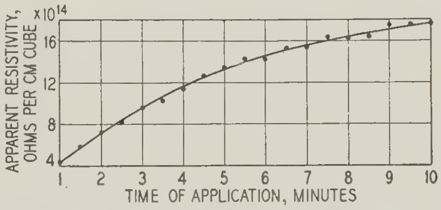


Fig. 2. Change of apparent resistivity of a length of paper cable with time of application of potential at end of drying period

Direct potential 220 volts
Apparent conductivities at ends of curve 2.3×10^{-15} and 5.6×10^{-16} mhos per centimeter cube

have been comparable to the value of 2×10^{-17} mho per centimeter cube reported by him.

Therefore it seems that electrical data obtained at the end of the drying period on Whitehead's samples agree very closely with corresponding data on a full sized length of commercial cable in regular manufacturing practice.

D. W. Roper (Commonwealth Edison Co., Chicago, Ill.): It is particularly interesting to note that the dielectric loss of the paper is improved by very low pressures during the evacuating process, that is, during the removal of the air and moisture, and, further, that the power factor-temperature curve slopes downward from room temperature to a minimum at about 70 degrees centigrade. A previous paper ("The Dielectric Losses in Impregnated Paper," J. B. Whitehead, A.I.E.E. TRANSACTIONS, volume 52, June 1933, page 673) reported that when the paper was impregnated with high grade, low loss oil, the power factor-temperature curve of the impregnated paper was determined largely by the curve of the paper. The conclusion is, therefore, readily reached that if a manufacturer utilizes a very low vacuum in removing the air and moisture from the paper and in addition uses a high grade, low loss oil, the power factor-temperature curve of the impregnated paper will slope gently downward from room temperature to about 60 degrees centigrade. This is exactly what is found in the highest grade impregnated paper insulated cables now being furnished by American manufacturers.

Apparently it is not feasible to make any further reductions of consequence in the dielectric loss of the ordinary type of impregnated paper insulation, as cable having a power factor at the maximum operating temperature of $^1/_2$ of 1 per cent or lower is now being furnished on commercial orders. In fact, the minimum values of power factor at the maximum operating temperature are below the corresponding values for oil-filled cable obtained a few years ago. It appears that if necessary we might even make some slight sacrifice in dielectric loss in order to secure increased stability of impregnated paper insulation.

A careful examination of several scores of samples of cable that has been aged in service or in an accelerated aging test shows that the deterioration invariably starts in the film of oil between successive layers of paper or in the small mass of oil between adjacent turns of the paper tape in one layer. As the deterioration of the oil proceeds, signs of deterioration may be noted on the surface of the paper tapes. One cause of this phenomenon may be explained as follows: The dielectric constant of impregnated paper is about 4 (4.83 at 60 degrees centigrade as determined by equations 1 and 2 of the paper by J. B. Whitehead previously referred to) while that of the oil is about 2.3. The successive layers of impregnated paper and the intervening films of oil can be considered as condensers in series between the copper conductor and the lead sheath, and successive layers of oil and impregnated paper will divide the stress in the inverse ratio of their dielectric constants. The dielectric strength of the oil is only about half that of impregnated paper, and so this difference in the dielectric constants of the 2 materials results in the greatest stress being placed on the oil which is least able to stand it. If an oil could be obtained having an increased dielectric constant, other properties remaining about the same, then the result would be that the stress on the oil would be reduced and the stress on the paper would be increased. This, of itself, would result in a considerably improved stability of the insulation.

Quite recently several of the leading oil refiners have introduced a new process of

petroleum refining by means of selective solvents, and it appears that it will be possible to secure presently an insulating oil that will increase in resistivity when subjected to the standard oxidation test (patent number 1,969,737 issued Aug. 14, 1934). This kind of oil would probably be more stable than the impregnating oils that are now being used. In addition, one refiner advises orally that he is getting, as a by-product of his process, a compound which has a dielectric constant between 4 and 6 as compared with about 2.3 for ordinary insulating oils. An ideal oil would be one having both of these properties, that is, an increase in resistivity under the standard oxidation test and a dielectric constant of about 4 or 5. Apparently, therefore, the long series of research papers by Dr. Whitehead and his associates has not exhausted the subject.

J. A. Duncan (Brooklyn Edison Co., Brooklyn, N. Y.) and **R. N. Evans** (nonmember): In the section on theoretical discussion the authors state that "It is surprising to find the simple relationships between moisture content and electrical properties indicated in this study" and that "while as yet no obvious explanations have suggested themselves, these simple relationships seem to indicate clearly that the phenomenon of adsorption of moisture by the fibrous materials commonly used in insulation is much more regular than heretofore supposed." The relation of moisture content to pressure as given in the section under that heading is $M = KP^n$. Since n and K are constants we may make the substitutions $n' = \frac{1}{n}$ and $k = K^{1/n}$. Then, on extracting the nth root of both sides of the equation, it becomes $M^{n'} = kP$ in which form it bears a striking resemblance to the Freundlich equation for adsorption isotherms. The only point of difference is that in the Freundlich equation P is the partial pressure of the adsorbed gas while in the authors' equation P is the total pressure. It seems not unlikely that the partial and total pressures might be linearly related in which case the equations are identical in significance as well as form. One need therefore not be dismayed at the simplicity of the result but should interpret the fact that a well-known relation is obtained by a new and independent method involving no direct determination of moisture as a confirmation of the reasonableness of the method.

Cable System Neutral Grounding Impedance

Discussion of a paper by J. E. Clem published in the January 1935 issue, pages 30–40, and presented for oral discussion at the cables session of the winter convention, New York, N. Y., January 24, 1935.

W. F. Davidson (Brooklyn Edison Co., Brooklyn, N. Y.): The author states in his summary that the proposal to limit the calculated arcing ground voltages to 3 times normal line to neutral voltage has been "accepted by the operators." What is his authority for such a statement? The committee on high tension cable of the Association of Edison Illuminating Companies has assigned to its subcommittee on research the responsibility of studying the cable grounding problem and as chairman of that subcommittee I do not know of any acceptance of this proposal. In fact, suggestions have been offered that would involve a somewhat different basis for determining the need for extra insulation between conductors and ground.

The author apparently assumes that arcing ground voltages are necessarily of appreciable duration for he makes no other reference to the effect of time that would have an important bearing on any determination of the voltages cable insulation might reasonably be expected to withstand. To my mind it is rather dangerous to proceed along this line of argument to the exclusion of others because it seems not inconceivable that, for certain cases at least, designs insuring rapid disconnection in faulty circuits may be more economical than providing the extra insulation that might be deemed necessary if arcing ground conditions were allowed to continue for appreciable periods of time.

Furthermore, the analysis used is directed to a determination of the conditions of neutral impedance which change the arc discharge at the fault from nonoscillatory to oscillatory. Now it seems to me that this limit will be influenced in important measure by the circuit constants at high (oscillatory) frequencies and that the author's use of 60 cycle constants with main simplifying assumptions may defeat the very purpose of the study. As an example, I would refer to some measurements of impedance to residuals recently made on 27 kv transmission cable circuits which show 2 resonance points in the frequency range from 60 to 3,500 cycles. Therefore, I am doubtful of the soundness of the conclusions as a basis for engineering design.

C. L. Gilkeson (Edison Electric Institute, New York, N. Y.): This paper is based upon the assumption of a particular type of mechanism by which an overvoltage is built up through a step by step process caused by the periodic extinction and restriking of an arc. The conclusions as given in this paper are entirely dependent on the overvoltages being produced by this mechanism, and the author admits that it is rather difficult to understand how an arc will be extinguished at the point of maximum voltage and not restrike until the voltage has built up on the next cycle to a value higher than that at which the original breakdown occurred. Furthermore, automatic records obtained during operation on open wire lines, as presented in a recent paper by P. A. Jeanne and myself ("Overvoltages on Transmission Lines," Electrical Engineering, Sept. 1934, pages 1301–9) and staged tests and laboratory measurements by other investigators, show no evidence of such a mechanism.

As a reason for considering arcing ground overvoltages the author points to the fact that higher values of insulation are ordinarily recommended for use on an isolated rather than on a solidly grounded system, and states that flashovers from time to time on partially grounded systems, not otherwise explainable, indicate that the possibility of arcing ground overvoltages cannot be disregarded. However, he neglects to call attention to the most common cause of overvoltage on a power system, aside from lightning and switching surges, namely, the shift of the neutral point. For known fault locations, calculations of voltage by the method of symmetrical components on an extensive high voltage aerial system operating with ungrounded neutral has given values up to 2.7 times normal phase to ground voltage. These are in good agreement with the measured values. The maximum dynamic voltage measured on this system was 3.9 times normal and was essentially of sine wave shape. The location of this fault was not known, therefore, no calculations were made to compare it with. Based upon observations of arcs in air and the extensive data on overvoltages on operating transmission systems I believe that periodic extinction and restriking of an arc at intervals of approximately a cycle is very unlikely, unless the arc is confined.

This is, of course, the condition that may exist for faults to ground on cable systems. Unfortunately we do not have any test or automatic measurements on a system consisting entirely, or even largely of cable; however, it would not be surprising to find voltages of much higher value than those observed on open wire lines, or to find that these voltages were of higher frequency than that of the fundamental of the supply system. Such a condition might result from series circuit, resonant at a frequency set up by the unstable condition of a confined arc in a good deionizing medium (an arc in an impregnated paper cable). Since such a series circuit may have low losses, high voltages might be encountered across certain parts of the system. However, voltages produced in this manner would not be calculable by the methods given in this paper.

Resistance and Reactance of 3-Conductor Cables

Discussion of a paper by E. H. Salter, G. B. Shanklin, and R. J. Wiseman published in the December 1934 issue, pages 1581–9, and presented for oral discussion at the cables session of the winter convention, New York, N. Y., January 24, 1935.

R. W. Atkinson (General Cable Corp., Perth Amboy, N. J.): The authors refer to what appeared at first to be a very adequate explanation of the variation of a-c current losses with the direction of phase rotation, this apparently being related to the direction of energy flow. Theoretical analysis then showed that this could not be. The losses are purely a function of current relation and are in no way related to voltage. As power flow brings in the relation of voltage phase the losses cannot be related to it or to its direction of flow. A fairly simple analysis along this line showed that the explanation of this curious phenomenon must be found elsewhere.

An explanation given in the paper for

differences in the proximity losses of certain types of strands appears to us to be susceptible of a similar definite disproof. This matter is presented in a separate discussion by Meyerhoff.

The mechanical disruptive tendency caused by heavy currents in the conductors of a 3 conductor cable was given much consideration by our company when the first type *H* cable was produced. At that time we made a number of tests leading to conclusions largely in agreement with those expressed in this paper. For instance, the conclusion that for currents up to about 20,000 amperes the lead sheath is itself adequate to resist the disruptive forces is identical with our own conclusion, our records being expressed in very similar language. Since, very commonly, short circuit currents are limited to values less than this, difficulties from this cause will ordinarily not be encountered. A very considerable number of the users of such cable, however, have raised the question as to the effect of currents greater than this.

In view of these things and of the nature of the results found, some of the data of our tests will add an important element to the information given by those authors. We also were limited to test currents of about 10,000 amperes and also found no distortion of the sheath with that current. In order to simulate the effect of currents considerably greater, we removed various amounts of the sheath, leaving circumferential rings at spaced intervals. Thus with rings 1 inch in length and spaced 8 inches between centers, we found a large distortion of the sheath with a current of 10,000 amperes, the resultant effect being comparable to what would have been obtained with 29,000 amperes with the full sheath. When 1 inch bands were spaced 5 inches apart, there was no distortion, this being equivalent to about 22,000 amperes on a complete sheath.

These tests were made on 3 conductor 4/0 cable, each conductor being insulated with $^4/_{32}$ inch paper insulation without belt and with a sheath $^5/_{32}$ inch thick, the outside diameter being 1.72 inches. It is to be noted that the disruptive forces for a given current would be greater with this conductor than with a larger one with thicker insulation, but that the restraining force of a $^5/_{32}$ inch thick lead sheath on this diameter would be considerably greater than with a sheath thickness usual for this diameter, and that it would be more effective for restraining distortion than a sheath of the same thickness and of a greater diameter. Thus, in general, the data applying to this cable are approximately directly transferable to usual commercial cable.

In view of these tests we believed that where a current over 20,000 amperes might occur it would be necessary to use a metal binder tape having a strength per unit length of cable considerably in excess of that of the lead sheath. We selected for the purpose a 3 mil steel or bronze tape. It seemed that only in exceptional cases might it be necessary to go to a 4 or 5 mil metal tape. However, the cloth tape sometimes suggested adds too little to the strength of the sheath to be considered as a reinforcement. It has the further disadvantage of sacrificing much of the gain of current carrying capacity which the type *H* construction normally gives.

There was found during these tests an effect not discussed by the authors which is very significant. The single phase tests which we made were with the current flowing in one conductor and returning in another, the third being idle. When sufficient current was applied, the effect produced was to throw the conductor out of the symmetrical equilateral arrangement. While at the time we were primarily concerned with type *H* cable, the results of this test are perhaps even more significant with regard to the belted type of cable. Even a slight distortion of this sort in belted cable would greatly weaken electrically the internal structure of the cable for tangential stresses and greatly magnify those effects for the elimination of which the type *H* cable was produced. It seems very probable that an effect of this sort may have had very much to do with the much poorer performance found for high voltage belted type cables than was anticipated from laboratory tests. This may also have had an important bearing upon the fact that although the initial operation of such high stress belted cable was initially very satisfactory, the failures of these installations were very severe and complete after trouble once started. Perhaps the distortions occasioned by the short circuit currents of the earliest failures resulted in rapid deterioration and consequent extensive failures of the rest of the system.

Louis Meyerhoff (General Cable Corp., Perth Amboy, N. J.): On page 1587 of the paper it is stated: "Rolling or crushing the conductor will increase the area of strand contact and reduce the concentration of current. The more compactly the strands are crushed, particularly the outer layers, the greater will be the reduction in proximity loss." I cannot agree with this statement. While it is true that crushing will reduce the concentration of current, it is also true that the amount of current will increase due to reduction of contact resistance. The induced voltage causing proximity effect is, of course, independent of contact resistance. Due to the fact that the contact resistance is fairly high, reactance plays a negligible part in determining the proximity effect current. This current will be determined practically altogether by the resistance and will thus be substantially in phase with the voltage. The current will therefore increase as contact between strands is improved and the loss, which will be substantially equal to the product of voltage and current, must also increase with improved contact.

This matter may be analyzed from another viewpoint. We have a 3 conductor cable carrying 3 phase current. The current in any one conductor may be regarded as composed of 3 separate currents, one of which is the main current from the applied voltage. The other 2 may be termed parasitic currents. One of these is caused by the electromagnetic action of the current in the conductor itself, its effect being known as skin effect. The other is caused by the electromagnetic action of the current in the other 2 conductors, its effect being known as proximity effect.

The current producing proximity effect or proximity loss is a circulating current which flows in the same direction as the main current in the part of the conductor near the center of the cable and in the opposite direction in the part of the conductor remote from the center of the cable. The proximity loss can be calculated accurately for solid round conductors. If instead of a solid conductor, we use a stranded conductor in which the strands are all parallel to the axis of the conductor, the proximity effect will be the same as for a solid conductor, and this would be true even though the individual wires were completely insulated from each other, as by enameling. The circulating current would simply flow in one direction in one part of the conductor cross section over the entire length of the cable and return in another part of the cross section, thus completing the circuit.

If, however, spiral stranding is used, again assuming perfect insulation between strands, there will be a tendency for current to flow in one direction in the part of an individual wire which lies on one side of the conductor and in the opposite direction in the part which lies on the other side of the conductor, with the result that no circulating current at all will flow, and the proximity effect will be zero.

In ordinary cable conductors the stranding is spiral, but the individual wires are not insulated from each other. The circulating current will tend to flow longitudinally from wire to wire, but there is considerable resistance to such longitudinal current flow, with the result that proximity effect in ordinary stranded conductors is always greater than zero but is never as great as in solid conductors.

The usual method of stranding is to spiral successive layers of wire in opposite directions. With this arrangement the proximity effect current has 2 paths which it may follow. One of these is longitudinally from wire to wire. The other is a zigzag path, following first along a wire in one layer, then along one in the next layer, then again along a wire in the first layer, etc. As the second path includes far fewer contacts between wires per unit length of cable than does the first path, the second path will carry by far the larger part of this circulating current. It may be expected that crushing or rolling the stranded conductor should reduce the contact resistance between adjacent wires and layers. Reduced contact resistance should increase the proximity loss. This conclusion is directly opposed to the quoted statement by the authors. It is not clear whether the authors' statement is based on experimental data or on theoretical considerations. If based on experimental data, it is clear that other conditions must have influenced the result, as, for example, shorter stranding length lay in the more crushed conductor.

Where the stranding is such that all of the wires are spiraled in one direction, only one path is available for this circulating current, that path being from wire to wire longitudinally. In conductors stranded in this manner the proximity effect has been found to be practically zero even when the conductor has been thoroughly crushed and rolled. While the crushing and rolling has undoubtedly decreased the contact resistance very materially there still appears to be high enough contact resistance so that there is no measurable proximity effect.

One of the coöperating laboratories mentioned in the paper is conducted by the

cable company which I represent. Most of our work was with conductors stranded in one direction, this being our normal construction. Our data on proximity effect of this type of strand are in complete agreement with the data reported. With this type of strand we also found, contrary to what was found elsewhere with the other type of strand, that proximity losses were no greater for nonimpregnated than for impregnated cable. This corroborates further the evidence that with this type of strand, contact resistance is much more than adequate substantially to eliminate proximity effect.

H. B. Dwight (Massachusetts Institute of Technology, Cambridge): The accurate measurement of the a-c resistance of 76 samples of power cable is a very large piece of work but it has been well worth doing since it has evidently disclosed practical forms of 3 conductor cable which, for large sizes, have approximately 10 per cent less resistance for 60 cycle current than other more common forms. To make a cable in such a way is equivalent to enlarging the cable 10 per cent at little or no increase in cost.

It might be of theoretical interest to measure the a-c resistance of cables with enameled strands, some with alternate layers laid in opposite directions and some with all layers in the same direction, to see if the crossing of the strands produces a type of local eddy currents when the strands are not in contact.

Dielectric Strength of Mineral Oils

Discussion of a paper by F. M. Clark published in the January 1935 issue, pages 50–5, and presented for oral discussion at the cables session of the winter convention, New York, N. Y., January 24, 1935.

C. S. Sprague (Purdue University, Lafayette, Ind.): This article represents a considerable contribution to our present knowledge of the mechanism of breakdown of liquid dielectrics and of the factors upon which their dielectric strength depends. Although the author has confined the work to the "uncontaminated" but "impure" oils, the correlation between the dielectric strength and the per cent air solubility or relative oil-dissolved air density is quite convincingly demonstrated.

With reference to figures 2 and 4 of the paper, the dielectric strength curve and the relative oil-dissolved air density curve for transformer oil show the same general shape with maximums at the same temperature. It may be assumed that the relative oil-dissolved air density curve for viscous cylinder oil would be similar in shape to curve *B* of figure 2. If this is true the writer would like to inquire as to the physical factors of the oils, outside of the different viscosities, which cause such a difference in the relative oil-dissolved air density curves. Why does the per cent air solubility decrease above 100 degrees centigrade, and would the relative oil-dissolved air density curve for viscous cylinder oil show a maximum at some other, say a higher, temperature?

The effect of temperature upon the dielectric strength of oil brings to mind an experience of the late Dr. H. B. Smith. With a large quantity of oil stored in an open tank, and with the oil temperature maintained a few degrees above room temperature by means of a small heating unit, it was observed that the dielectric strength of the oil showed a slow but definite increase over a period of time. Probably this same effect has been noted by others. At the time it was considered that slight traces of moisture might be evaporating from the surface of the oil due to its higher temperature but as shown by the author the increase in the dielectric strength might have been caused, in part at least, by a greater air solubility.

The continuation of work such as this is much to be desired and should provide a basis for the classification of the several types of impurities and contaminants, and for determining the effect of each type upon the dielectric strength of the oil. Some tests are being made at Purdue University using both 60 cycle and impulse voltages to determine the effects of different temperatures and varying degrees of contamination. While no conclusions are available at the present time, it is evident that in such work as this the nature of the contaminants must be known. It would seem quite probable that with certain types of contaminants, the increase in dielectric strength from greater air solubility at the higher temperature would be more than offset by a decrease in strength from the contaminant.

J. B. Whitehead (The Johns Hopkins University, Baltimore, Md.): This concise and interesting paper shows a correlation between the laws of breakdown of oils containing substantial amounts of air and the corresponding laws for the breakdown of gases. It is my understanding that the author feels that the breakdown of such liquids may actually be determined by the laws for gases as applied to the gas absorbed in the oil. The outstanding correlative feature is the increase in dielectric strength of the oil with increasing relative density of the absorbed air.

It is doubtful whether such a proposal can be successfully defended in the face of much other evidence. For example, experimental determinations of the relationship between dielectric strength of an oil and pressure vary widely, are difficult to repeat, and are known to depend particularly on traces of impurities and on the conditions at the electrode. The impulse breakdown of an oil is independent of the pressure and, within wide limits, of the dissolved impurities. More particularly, however, oil breakdown is essentially an ionization phenomenon, and the current-voltage characteristic involving the saturation and ionization regions is entirely independent of the applied pressure. Over a variation of pressure, breakdown will occur at different values of applied voltage, but the current-voltage curve up to breakdown remains the same. If the amount of contained gas is an element in the ionization process, we should expect a corresponding variation in the current-voltage curve. Furthermore, remembering the differences in density in the oil and in the absorbed air, and the relatively small proportion of the latter, it is difficult to picture an ionization process involving only the widely scattered molecules of the gas, and which is independent of the far greater number of intervening heavier liquid molecules.

It is regrettable that the author has not presented more experimental data. Those given are too few to warrant the statement of a definite law. In particular, the experiments of Kock utilized by him were made under conditions which make them unsuitable for the author's purposes. In Kock's experiments, the pressure was varied hydrostatically and the amounts of absorbed air were presumably constant. Moreover, his oils were free of gas.

Nevertheless the experiments quoted do indicate the type of correlation proposed by Clark. No certain explanation suggests itself, but I offer the following: Assuming that the stability of the atom of oil is the determining element in the process of secondary ionization, and remembering that this process involves the splitting off of an electron, it may be safely assumed that the outermost or most loosely bound electrons in the atom are those that are involved. Now these are also the electrons which are probably most actively involved in chemical combination. Oxidation is one of the most active and powerful of such chemical processes. If, therefore, we assume that the effect of increasing quantities of air is simply to afford increased amounts of oxygen available for tying down or restraining an increasing number of otherwise loosely bound electrons, fewer and fewer of such electrons would be left for the ionization process and consequently the probability of secondary ionization and breakdown would be lessened as the amount of dissolved air increased. A test of this proposal could be made by experiments using a number of different gases, among them inert gases or others known to offer little possibility of chemical reaction with the oil atom.

F. W. Godsey, Jr. (Sprague Specialties Co., North Adams, Mass.) and **Preston Robinson** (nonmember): The data presented in this paper show remarkably close agreement between gas laws and dielectric strengths of liquids. The dependence of dielectric strength upon the number of molecules of gas per unit volume of the liquid, or the relative liquid-dissolved gas density *D* as used in equations 2 and 3, should prove a useful relation in attacking insulation problems.

Unless the agreement between theory and experiment in the middle range of pressure investigated is of a most unusual accidental nature, differences at high pressures between theory and experiment may be so because air is not a perfect gas, especially at the higher pressures.

The only results reported upon are for equilibrium conditions between a gaseous atmosphere above the oil and dissolved gas in the oil. What will be the effects of unsaturated and supersaturated solutions of gas in oil upon equations 2 and 3?

These relations indicate that dissolved gas ions are not closely attached to molecular groups in the solvent, but have a freer distribution in which gas ions may move about

with comparative freedom. They also indicate that ionization leading to breakdown in oil is initiated by relatively light weight gas ions acquiring high velocities from electric fields imposed on the oil. Even though collisions between ions and molecules occur frequently, these collisions are elastic and ions lose a very small percentage of their previously acquired energy in such collisions because of the large difference in mass between ions and oil molecules. Ions may then gain in kinetic energy through potential drops until sufficient velocity is reached to result in inelastic collisions and ultimately, cumulative ionization leading to breakdown. As an aid to this process, ionization potentials of molecules are lowered in a medium of higher dielectric constant than air.

Assuming average values of molecular weight of oil M at 250, the mean free path λ of an electron 5×10^{-7} centimeters, and an electric field gradient X of 50,000 volts per centimeter, Compton's equation

$$U_t = \frac{\Omega}{2} + \sqrt{\frac{\Omega^2}{4} + \frac{\lambda^2 M X^2}{4.536\ m}}$$

will yield the terminal velocity of the electron U_t in volts. In the equation Ω is the molecular energy in volts and can be neglected here; m is the molecular weight of an electron. With the above values substituted in the approximation equation

$$\Omega_t = \sqrt{\frac{\lambda^2 M X^2}{4.536\ m}}$$

a terminal electron voltage of 8 volts is obtained. It is significant that this is approximately the ionization voltage of many substances.

With extension of tests to conditions of unsaturated and supersaturated solutions and further evidence in connection with an hypothesis that suggests itself, namely that hydrostatic pressure of the liquid does not influence the effective gas pressure, these relations discovered by Clark should be useful in a revision of our previous ideas concerning the nature of dielectric losses in insulating liquids.

Overvoltages on Transmission Lines

Discussion of a paper by C. L. Gilkeson and P. A. Jeanne published in the September 1934 issue, pages 130–19, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

Edward Beck (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): An important aspect of this paper is the bearing on the application of lightning protective devices such as lightning arresters, which are designed to clear, subsequent to a lightning discharge, system voltage between line and ground up to a magnitude defined in the arrester rating. The paper gives corroboration by actual measurement of conclusions reached from theoretical studies, such as those made by Wagner and Evans, namely that conditions exist under which the normal, dynamic voltages from line to ground may become very much distorted; in fact, to such a degree that the maximum voltage ratings of arresters normally applied may be exceeded. For instance, in the case pictured in figure 10 of the paper, a 26 kv system, it would be quite usual unless the system had been studied to apply arresters rated 30 kv maximum. The figure indicates that the voltages to ground up to $26 \times 0.58 \times 2.5 = 37.7$ kv may occur, exceeding the arrester rating by 7.7 kv or 20 per cent. This would expose such an arrester to the hazard of failure, if a surge sufficient to discharge the arrester should occur during the existence of this distorted condition.

Fortunately, the probability of occurrence of a high degree of voltage distortion is small, as indicated by the data in the paper; thus the hazard of arrester failure from excess dynamic voltage is also one of probability. However, arrester failures have occurred as a result of the conditions discussed. It is interesting to see in the paper convincing evidence of these voltage distortions.

The writer does not intend to promote the use of high rated arresters on systems except under special conditions. However, he does wish to point out that certain voltage conditions must be taken into account in the application of arresters. From this aspect the paper contributes to a thorough recognition of this factor in choosing lightning arrester ratings. The rating chosen will in the end be a compromise between protective ratio, cost, rating, and estimated risk of arrester failure.

The writer is of the opinion that these conditions exist with greater prevalence on the lower voltage distribution systems than on high voltage transmission lines and that close applications of arresters even on grounded neutral systems are not generally advisable. Measurements of voltage distortion existing in the vicinity of faults, caused by the voltage drops in the earth resistance of the fault would be of interest since they may theoretically cause in the vicinity of a fault full phase to phase voltage to appear from the sound lines to earth. We would like to ask if the authors have any information on this phase of the problem.

J. O'R. Coleman (Edison Electric Institute, New York, N. Y.): I would like to emphasize the qualification which these authors make at the beginning of the paper, that their work has been confined to systems consisting almost entirely of open wire transmission lines. In a cable system it should be noted that the relative magnitudes of the fundamental constants are entirely different. The ratio of inductance to capacitance, as well as the relative losses in any self-resonating circuit consisting of these quantities, would be much less for a cable circuit than for an open wire line. It should also be recognized that the behavior of an arc in air and the behavior of an arc confined in a deionizing medium, such as cable paper, has an entirely different behavior. Some time ago I learned of overvoltages on cable circuits under certain specified conditions which apparently well exceeded the voltages which Gilkeson and Jeanne have observed in their work. It is my understanding that this phenomenon is now being investigated and I hope the engineers will have an opportunity to study it fully so that they can give us the benefit of their work.

Constant-Current D-C Transmission

Discussion of a paper by C. H. Willis, B. D. Bedford, and F. R. Elder published in the January 1935 issue, pages 102–8, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

E. F. W. Alexanderson (General Electric Co., Schenectady, N. Y.): Stone has pointed out one of the objectives of this development, which is to reduce the cost and increase the range of electric power transmission by the use of d-c underground cables. I wish to point out another objective. Electronic converters of various forms have been described in several papers presented to this convention. It is a common feature of all these that they can serve to transfer power from one system to another without regard to synchronism. We have thus 2 objectives: the improvement of the transmission line and the freedom from the limitation of synchronous operation. Each of these is a separate problem which can be analyzed on its own merits. It is, however, significant that the electronic converter offers the solution for each of these problems, either separately or in combination.

W. M. Goodhue (Harvard University, Cambridge, Mass.): The properties of monocyclic networks discussed by the authors are particularly interesting in their application to rectifiers and inverters for the purpose of obtaining constant direct current for the transmission of power.

There are, however, some factors which the authors have not discussed. The system is a constant current one. When a d-c line wire breaks, or the d-c circuit is in any way interrupted, the system still attempts to maintain constant current. With the very high resistance introduced by the break, the voltage will also increase to very high values. Furthermore, the ordinary monocyclic network has practically an infinite open circuit voltage, which would puncture the condensers or cause the tubes to arc back, or damage the power transformers. It would seem that some protection against this occurrence would be necessary.

It would also be interesting to know whether or not the circuit will operate in an interconnected d-c transmission system. If the currents of the monocyclic networks regulate to a nearly constant value, the resulting interconnected d-c systems will show instability due to the independent current regulation of the several systems.

The inverter will also produce harmonics of considerable proportions and of a wide range of frequencies. These harmonics must be eliminated in order to supply a reasonably good wave form to the ordinary a-c distribution networks at the receiving end of the d-c transmission line. Also,

the harmonics cannot be tolerated because of telephone and radio interference. It will probably be impracticable to eliminate these harmonics by the use of ordinary filters, since such filters for an a-c system would be too costly.

It also seems that the use of capacitors of full kva rating in a power system is objectionable because of the danger of puncture (not surge proof, like electrolytic condensers which are generally suitable for d-c only), and also because of the cost. A condenser for use in resonant circuits such as monocyclic networks must have a very stable dielectric, such as low dielectric constant impregnated mica or paper.

It also appears questionable whether or not tubes are suitable for large power systems. The oxide coated cathode, and sealed vacuum chamber would seem to be too delicate. Something in the nature of a steel tank rectifier with mercury pool cathode would seem to be more appropriate.

A. W. Hull (nonmember): Many may wish to ask whether grid-controlled vapor-discharge tubes have attained sufficient reliability for this service, for the fact that they have been successful in railway work does not guarantee their applicability to the higher voltage and more exacting requirements of power transmission.

The answer to this question depends not only upon the tubes but upon the circuit. The constant current circuit described by the authors is unique in its fair treatment of tubes. They are never out of work; never overloaded, even during a circuit fault; and they are not punished if they fail. The tubes respond by correspondingly good behavior. The 3 causes of tube trouble in constant potential operation are idleness, overload, and severe punishment (20 to 30 times normal current) in cases of failure. Idleness is the most serious of these, as experience shows that the majority of failures occur after a period of no current.

The reliable tube operation which we have experienced is therefore due in large measure to the "good working conditions" furnished by the constant current system; and the authors are to be congratulated on this feature of their circuit.

C. W. Stone (General Electric Co., Schenectady, N. Y.): The authors, in their description of this new system, are most modest in their statements and I would like, therefore, to point out some of the essential features of this circuit which should be of great importance to the electrical industry.

One outstanding feature is that for the first time in the transmission of electric power (except with the Thury system), full control of the amount of power and the direction of the power flow is obtained. The value of this characteristic of the circuit is so great that a paper could be written on this phase of the subject alone.

As the system described is a nonsynchronous tie, the inverter is always in phase with the system to which it is connected and the frequency of the system can be like or unlike that of the system feeding the rectifier.

Major disturbances which take place on existing systems, such as short circuits which tend to pull the system apart, cannot take place if this system of transmission is used.

Heretofore, it has been difficult to maintain operation of an inverter circuit feeding into a system of lagging power factor, but apparently by the use of the monocyclic network, this particular feature is completely overcome as the circuit automatically adjusts itself to feed a load of any lagging power factor.

Both the rectifier and the inverter receive constant current. Thus, on any failure in either the rectifier or the inverter circuit, the current is limited to full load current and the power flow is always reduced.

Since this paper was prepared, a much larger circuit has been built and has been in successful operation for several months. In this case, the circuit is of 3,000 kw, operating at 15,000 volts, 200 amperes, and the results obtained to date would indicate that all the facts illustrated by the authors in their paper describing the 150 kw circuit apply equally well to this circuit of larger size.

Engineers might be inclined to hesitate to use electronic devices for large power transmission, but all indications to date are that, with this circuit, such devices can be operated for large powers, both in rectifiers and inverters, with reliability of a high order.

I would like to call particular attention to the very high efficiencies obtained; that is, conversion from constant potential to constant current, or the reverse, can be obtained with losses little greater than those usually realized in efficient transformers heretofore built.

The losses in the particular tubes used in the 150 kw outfit described by the authors and in the larger tubes used in the 3,000 kw outfit are so small that they can be neglected.

It would appear that this system of transmission is particularly applicable to underground cable installations.

Philip Sporn (American Gas and Electric Co., New York, N. Y.): The fundamental idea of constant current transmission is not new, of course; the Thury constant current system has been in use for many years. That part of the system described by the authors which is new, however, is the use of grid-controlled vapor-discharge tubes and the newness consists specifically in the utilization of a soft circuit for heavy tube work.

Those of us who have been working with and trying to find applications for these tubes for the last 5 years or so have felt all along that the tubes had many possibilities; possibilities, it sometimes seemed, the surface of which has been barely scratched in the applications developed to date. Perhaps some of the difficulties in this regard have been due to the slow development of the tube itself; but whether because of that or whether because of the fact that the circuits heretofore developed have presented too difficult a problem for the tube designer, it is pertinent to note that the particular circuit described by the authors is less severe on tubes than any other circuit developed heretofore for any heavy tube application. It is possible, therefore, that this proposed scheme of d-c power transmission may offer one of the first really important and extensive applications for grid-controlled vapor-discharge tubes.

This scheme has, under proper conditions, some theoretically attractive advantages. In examining the possible gain in changing over to such a transmission system, let us consider an existing transmission line. If it is a single circuit, with 3 conductors and ground wire, and we assume that the d-c system is to be maintained in a balanced state with respect to ground, we shall be able to use 2 conductors with either the third conductor or the ground wire as a neutral conductor; and the power that can be transmitted, assuming d-c system voltage equal to a-c system crest voltage above ground, will be $2\sqrt{2}E_nI$ as compared with $3E_nI$ on an a-c system, where E_n represents the effective alternating line to neutral voltage, the current being the same in each case. Under these assumptions, the capacity of the d-c line will be only 94.3 per cent of the a-c line. However, if the d-c line can be operated at a higher voltage than this, as may be possible, then its capacity will be increased in direct proportion to the increased voltage.

A double circuit a-c line having conductors and one or more ground wires permits a more economical utilization of the conductors, as three balanced d-c circuits, each using the ground wire as a neutral, can be obtained. In this case, assuming as before that the d-c line will be operated at alternating crest voltage, the capacity will be $6\sqrt{2}E_nI$ as compared with $6E_nI$ for the a-c line. This represents a theoretical gain of 41.4 per cent in favor of the d-c transmission. Here again, if the voltage is increased, a corresponding further gain is obtained.

In the case of a single circuit installed on a line built for 2 circuits, it might be found economical to install a single fourth conductor in order to provide for 2 balanced d-c circuits, using the ground wire as a common neutral. This would double the capacity of the single circuit line described above. If d-c transmission ever finds extensive application, this might be a logical step to take in lieu of the installation of a second complete a-c circuit, since it would provide very nearly the equivalent of a double circuit a-c line by the installation of only one additional conductor. Further increase in capacity would then be obtained by the installation of the other 2 conductors.

It should be pointed out, however, that all these discussions are based upon a consideration of the transmission line itself, without considering the effect of the terminal equipment on the problem and on the economics of any particular situation. Thus, although it appears that a great gain in capacity can theoretically be obtained by the use of a d-c system, at the same time, when the job as a whole is set up and the costs of the additional terminal equipment are considered, the chances, so far as one can judge at the present time, are quite excellent that the balance would swing in favor of a-c transmission; for it must be remembered that with a system like the one described by the authors, a-c generation and utilization both would

still continue. This necessitates the extra cost of conversion and inversion equipment in the form of tubes, transformers, reactors, and capacitors. The cost of this equipment and the extent to which it can be reduced will be one of the major factors in determining the economic feasibility of the whole scheme. No actual data bearing on that having been presented by the authors, nor by anybody else, it is hard to pass judgment at the present time as to what the economics of the scheme are.

Even assuming that the economics are sufficiently in favor of this particular scheme of transmission, there are a great many other problems, some of them highly important, dealing with the performance of such a transmission system, which will have to be solved before it will be possible to consider the system seriously or sound from a technological viewpoint. Among these are the following:

1. It has been suggested that with d-c transmission the voltage on existing types of insulators can be raised to 50 per cent of the actual flashover voltage, since switching surges will not enter into the picture, and under the proposed constant current system, dynamic follow-up in flashovers cannot occur. This disregards, of course, the lightning angle. In this connection it should be pointed out that it has taken almost a decade of very intensive research and investigation to give us the knowledge of the performance of an a-c line under lightning conditions that we have today, with the result that although lightning in the past was one of the most difficult problems in a-c transmission, it has recently been brought fairly well under control, and the late developments in the construction of transmission lines, including the use of expulsion tubes of various types, have very nearly solved the lightning question on a-c lines. If d-c transmission is to be seriously considered, a complete investigation of lightning performance should be undertaken.

2. Even if it is granted that the circuit may permit the discharge of lightning potentials on a transmission conductor without materially affecting the power voltage proper over any length of time, it must still be remembered that very little is known about the performance of insulators under d-c voltage of high levels, and a great deal of research and investigation will be required on that. Thus, it is a well recognized fact that a high voltage unidirectional field will cause the precipitation of dust and other particles. The effect of this phenomenon upon insulators carrying a d-c transmission line, particularly in industrial region atmospheres, will have to be thoroughly investigated.

3. The corona situation will also have to be studied. The suggestion has been made that the effect of the unidirectional field around the high voltage d-c conductors in building up an ionized space around the conductor will provide automatically an equivalent increased diameter, thus making the corona effect more or less independent of the actual diameter. But here again much more work will have to be done.

4. Still another problem which will have to be solved in connection with large scale use of rectification and inversion equipments, such as are called for in this and every other scheme of d-c transmission, is the problem of harmonic distortion in both the a-c and d-c systems connected to this equipment and the resulting possibility of interference with communication systems. While it may be true that the filtering of the d-c circuits involved will be technically comparatively simple, the distortion of the wave shape on the a-c systems connected to the conversion and inversion equipments may present a rather serious situation, as evidenced by the interference difficulties which have been encountered in connection with some recent mercury arc rectifier installations. No doubt ways will be found of solving this problem, but its solution will constitute no negligible factor in the cost of equipment, and again may militate against the economic feasibility of the scheme.

In pointing out the economic considerations that will have to be taken into account and some of the technical difficulties that still stand in the way, I do not in any way want to detract from the credit that the authors of the paper are entitled to for carrying through a brilliant piece of research. But it behooves us to explore it from all angles in order to definitely determine what its possibilities for practical application are. Personally, while I believe that the system described has possibilities, I cannot see that any of the work that has been disclosed so far indicates that we are as yet on the threshold of a new era in transmission; and while the business of being a prophet always has been a dangerous business, and has been particularly so in the last 5 years, I venture to predict that in view of the many both economic and technical problems that remain to be solved, 10 years hence most of our power will still be transmitted as alternating current.

D. M. Simmons (General Cable Corp., New York, N. Y.): A vital element in considering the economics of transmission by direct current is a knowledge of the level of insulation required for this purpose. An inherent characteristic of impregnated paper insulation suggests the thought that underground paper insulated cables should offer great advantage for d-c transmission. In general the flashover in air for direct-current is about the same as the a-c crest value, namely, 1.4 times the effective a-c value. It was established some years ago that the breakdown strength of paper insulation under direct-current is 2.4 times the effective a-c value and this ratio is recognized in present cable specifications. The purpose of this discussion is to point out that the advantage for transmission is probably very much greater than would be indicated above.

The ratio of d-c to a-c breakdown strength of impregnated paper which is generally accepted was determined during the period when the voltage-time characteristics of a-c breakdown strength were not fully appreciated. In other words, paper insulation will stand a certain voltage for a certain period of time and a very different voltage for a different time, the differences being very great. Very little work has been done on the d-c voltage-time characteristics of impregnated paper. It is the general belief, and my own experience supports this fully, that the voltage-time curve of breakdown for d-c potential is almost a horizontal straight line, probably with a small drop for a very short time after application. A definite ratio of breakdown strength between direct and alternating voltages would be possible only if the 2 curves were parallel. Figure 1 of this discussion shows roughly the characteristics of the 2 potentials. It is quite obvious that a "ratio" is an untenable idea. There will be a different ratio for each period of time.

The ratio 2.4, as figured, was determined before such curves were available and was determined on short time tests. Insulation thicknesses, however, are determined as a percentage of the final low time value or breakdown strength for alternating-current. It will be clear from the figure that if 2.4 is the correct ratio for short time, as seems probable, the correct ratio for long time must be much greater than 2.4. The data is not full enough to make any definite suggestions, but the correct ratio of voltage to use for d-c transmission certainly must be greater than 2.4 times the a-c value and might be 4 or 5 times as great.

The above remarks apply to direct potential as such. With constant current direct potential, there is a new feature which still further improves the characteristics of impregnated paper cable. The chief enemy of a paper impregnated cable is the voids which are created by temperature cycles. In fact, when the creation of voids is prevented, as in an oil filled cable, stresses with alternating current may be used double the value which could be used where voids are produced by temperature cycles. With constant current transmission there will be no temperature cycles, except slight ones from seasonal variation. There is little reason to expect as great a gain in direct current by elimination of voids, but there will be some gain to be superimposed upon the gain obtained by reason of other causes. The idea is very alluring. Is it possible that the use of constant direct current may make it possible to rate a new solid type cable at 5 or 6 times its present voltage rating?

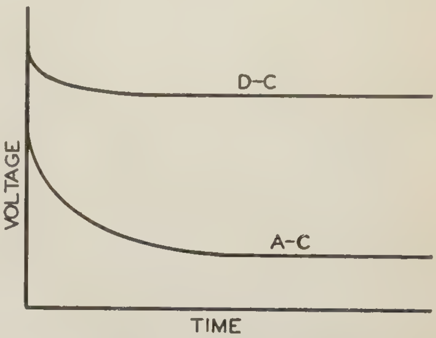


Fig. 1. Comparison of characteristics of cable insulation under alternating and direct current

Expulsion Protective Gaps on 132 Kv Lines

Discussion of a paper by Philip Sporn and I. W. Gross published in the January 1935 issue, pages 66–73, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): It is indeed gratifying to note the record of performance of the expulsion protective gaps. Since the close of the lightning season, development has been in progress having for its object the improvement of tube characteristics such that flashover under the extreme rain conditions mentioned in the paper would be confined to the inside of the tube.

As a result of this development, it is felt that a method has been found which will materially increase the ratio of the external to the internal flashover of the tube, and at the same time offer some improvement in protection characteristics.

The improved expulsion gap was used on some new installations made this winter, and their performance will no doubt be

reported to the Institute after sufficient lightning experience has been had with them.

Expulsion protective gaps will, in general, be called upon to discharge a smaller proportion of the current of the direct stroke on a system with steel towers and overhead ground wire, as described in the paper, than would be the case with steel towers but without overhead ground wires. This is because if lightning contacts the line wire a very large part of the current of the direct stroke must pass through the expulsion gap to reach ground, while if the lightning contacts a ground wire the expulsion gap passes only the impulse current flowing into the surge impedance of the line conductor, which will be of the order of 250 ohms. Of course, with high tower footing resistances, and without ground wires, the tube current will approach that of the case where the lightning strikes an overhead ground wire. In the limiting case of infinite ground resistance, the lightning tube current from the stricken phase will be equal to that allowed by the combined surge impedances of any other tubes which operate as a result of the elevation of the potential of the tower top.

The performance of the tubes on multiple strokes shows the necessity of including the effect of multiple strokes when considering the performance of protective devices. The expulsion gap appears to have given a good account of itself in this respect. Out of 11 multiple stroke records, noted in the paper, only one was unsuccessful. This is somewhat greater than the 7 per cent faulty operation given in the paper, although it is not definitely known that all of the successive discharges shown per phase passed through the same tube. It seems likely, however, that the great majority did.

For a given tower footing resistance, the use of expulsion protective gaps on one circuit of a double circuit steel tower line offers some protection to the unprotected circuit up to a certain limit of current. As the margin between the impulse flashover of the insulator string and the protective level of the expulsion gaps is increased, the current which can be discharged to ground without causing the unprotected circuit to flashover is also increased. This applies only where the lightning contacts the ground wire or tower, or similarly one of the phase conductors of the protected circuit, but does not apply if the unprotected circuit is struck.

To obtain some idea of the protection offered by the expulsion protective gaps to the unprotected circuit, calculations have been made for the Glenlyn-Roanoke circuit as it is, and for the same circuit with the line insulation increased from 10 disks spaced $4^3/_4$ inches to 10 disks spaced $5^3/_4$ inches.

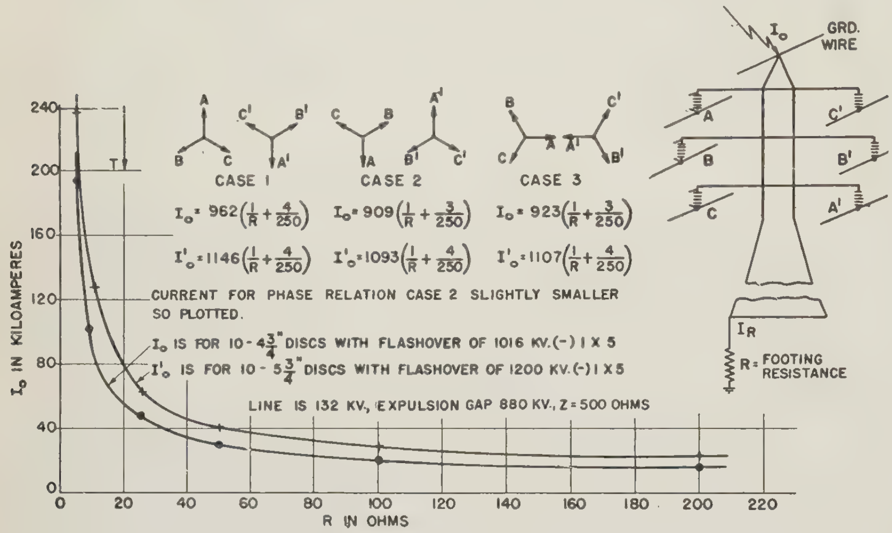


Fig. 1. Degree of protection offered 3 unprotected phases by 3 phases equipped with expulsion gaps on a double 3 phase transmission system

The assumption is made that lightning strikes the tower, raising its potential to an amount equal to the assumed current times the resistance of the tower footing and the surge impedance of the ground wire operating in parallel. Reflections over the ground wire from adjacent towers are not considered, since approximately 1.5 microseconds would elapse before any effect could be felt, and to include this effect would complicate the calculation considerably without materially changing the result since the calculations are based on the 1×5 microsecond wave. In making this calculation the negative flashover values used are based on those recently published by G. D. Heye ("Impulse Flashover of Suspension Insulators and Rod Gaps," *General Electric Review*, Dec. 1934, page 548) and are adjusted for change in string length.

Since it has been shown ("Multiple Lightning Strokes," K. B. McEachron, ELECTRICAL ENGINEERING, Dec. 1934, page 1633) that with negative impulse on the tower, flashover will occur first on those phases on which the power voltage is most positive, it is desirable to examine at least 3 values of instantaneous system potential for each conductor. The phase positions chosen are shown in cases 1, 2, and 3 in figure 1 of this discussion, where phase A is successively 107 kv positive, 107 kv negative, and 0. On the Glenlyn-Roanoke line the phase positions A, B, and C are reversed on opposite sides of the tower as indicated in figure 1.

Table I of this discussion shows the impulse potential which must be added to the instantaneous phase potential to cause flashover for each of the phases. For case 1, the instantaneous system potential is 107 kv positive so that a negative value of 773 kv impulse will cause the operation of the expulsion gap on phase A. Additional increase in potential causes the tubes on phases B and C to operate. If the current flowing into the ground resistance (assume 25 ohms) and into the surge impedance of 3 conductors and the ground wire exceeds approximately 54,000 amperes, then according to table I unprotected phases B' and C' will next flash, followed by A' if the current further increases.

For cases 2 and 3, however, 2 protected phases would flash first, followed by one unprotected phase when the total current equalled approximately 47,000 amperes. In this case the 2 phase conductors are carrying approximately 7,000 amperes. This indicates that a tower current of approximately 40,000 amperes would be required with a ground resistance of 25 ohms and one ground wire to cause flashover. It is interesting to note that the expulsion gap must be applied to all 3 phases to gain this increase in current to flashover, since there would be no certainty a single protected phase would be at a sufficiently positive potential to cause it to operate, before some other phase. It is necessary to have all 3 phases protected to be sure that 2 of them function before the unprotected phases flashover.

When the insulation is increased to 1,200 kv, an appreciable increase in protection results to the unprotected phases. The table shows that all 3 gaps will operate before any unprotected phases flash, which places a combined surge impedance of $\frac{250}{4} = 62.5$ ohms in parallel with the ground resistance. Due to the additional parallel path and also to the increased potential, a current of approximately 61,000 amperes would flow before the unprotected phases flashover. In this case, the ground wire and

Table I—Additional Impulse Voltage (1×5 Microsecond Wave) Required for Flashover of Various Phases

Phase	$4^3/_4$ Inch Spacing[1]	$5^3/_4$ Inch Spacing[2]	Instantaneous System Potential, Kv
	Kv	Kv	
Case 1			
A	(1)[3] 773	(1) 773	+107
B	(2) 934	(2) 934	− 54
C	(2) 934	(2) 934	− 54
A′	(4) 1,123	(3) 1,307	−107
B′	(3) 962	(4) 1,146	+ 54
C′	(3) 962	(4) 1,146	+ 54
Case 2			
A	(3) 987	(2) 987	−107
B	(1) 826	(1) 826	+ 54
C	(1) 826	(1) 826	+ 54
A′	(2) 909	(3) 1,093	+107
B′	(4) 1,070	(4) 1,254	− 54
C′	(4) 1,070	(4) 1,254	− 54
Case 3			
A	(2) 880	(2) 880	0
B	(1) 787	(1) 787	+ 93
C	(4) 973	(3) 973	− 93
A′	(5) 1,016	(5) 1,200	0
B′	(6) 1,109	(6) 1,293	+ 93
C′	(3) 923	(4) 1,107	− 93

1. Insulator flashover 1,016 kv.
2. Insulator flashover 1,200 kv.
3. Numbers in parenthesis indicate order of flashover.

the 3 protected phases carry away an impulse current of about 17,500 amperes.

The values given are somewhat pessimistic in that the reflections over the ground wire from nearby towers have been neglected. If flashover occurs on the front of the wave, which it may well do, the flashover values of the insulators will be increased more than the protective level of the expulsion gap. With steep waves, this gain will be offset to some degree by the time taken for reflections to travel over the length of the tower, which effect has been neglected for the conditions taken. In this discussion the effect of coupling has not been considered.

It would be interesting if the authors of the paper could check their data in those cases where 2 and 3 expulsion gaps operate, to see if one phase of the unprotected circuit flashed. The value of the tower current might also be checked against the lower curve given in figure 1 of this discussion.

E. M. Hunter (General Electric Co., Schenectady, N. Y.): The conclusion reached by the authors that the absence of external flashovers on the expulsion protective gaps would probably have resulted in 100 per cent lightning proof operation on these 2 trial lines during their first complete year of gap operation is interesting in that it suggests the possibility that a lightning proof line is at last obtainable at a reasonable cost.

In order to insure continuous service, it has often been necessary in the past to provide duplicate circuits with proper relays and oil circuit breakers so that short circuits caused by lightning may be removed with a minimum of system disturbance. This method of permitting a lightning surge to cause a short circuit before doing something about it requires that the faulty section of the system must be at least temporarily out of service.

A much better procedure would be either to prevent the lightning from striking the lines or to relieve the stress resulting from direct or induced strokes to the line without a line interruption. There has been a trend in the development in protection technique to do just these things.

Overhead ground wires in combination with low tower footing resistance, obtained with the buried counterpoise or other suitable means, tend to act as a shield to prevent the lightning surge from reaching the line conductors and building up sufficient voltage from tower to conductor to cause flashover.

The Petersen coil which has been used extensively in Europe and has had a limited acceptance in America does not prevent the lightning surge from getting on the transmission line, but it does remove all ground faults resulting from the surge without a breaker operation, provided no permanent damage is done to the line insulation.

The expulsion protective gaps also have no part in preventing lightning from getting on the lines, but do supply paths whereby the surges may be harmlessly passed to earth. Whereas the Petersen coil requires an isolated neutral system and is only suitable for removing ground faults of a temporary nature, the expulsion protective gaps will dissipate the energy of surges whether one or more phases are involved and they are applicable to the grounded neutral system which is in common use in America today. Thus, in many cases, these gaps should prove to be a worth while investment because their ability to interrupt a short circuit and restore service in a minimum time of one cycle or less should reduce the necessity for complicated relays, oil circuit breakers, and duplication of circuits to obtain continuity of service.

The general acceptance and use of the expulsion protective gap instead of other methods for mitigating transmission line troubles resulting from lightning will probably be one of economics. It is really too soon to draw any conclusions as to the total cost of using these devices, but the original cost for equipping any existing line probably will lie between the cost of installing the combination of overhead ground wires and counterpoises and the Petersen coils, the former probably having the higher cost. Thus, if the maintenance cost of the gaps is not too great, they should have a wide field of application.

Otto Ackermann (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): In the list of principal requirements for practical flashover protectors given in the beginning of the paper, the demand is made that "the tube installation . . . would have to be not only accessible, but easily removable to take care of . . . maintenance . . ." In this respect the 3 types of mountings shown in the paper are radically different. Tubes mounted below at an angle of 30 degrees as in figure 1 of the paper can be removed without taking the line out of service. With the mountings as in figures 2 and 3 this appears to be at least very difficult, whereas it seems to be almost impossible with the V mounting of figures 4 and 6.

Regarding the maintenance it should be remembered that, except possibly for the finish, the fiber tube bore is the only thing which is affected by the service and which finally limits the life of the protector due to the erosion which accompanies every operation. Although the number of operations per tube per year is small, the question will come up eventually of how much life is left in any particular protector and whether it should not be removed before failing. The deciding factor in this maintenance question is the actual diameter of the tube bore. Where the tubes are mounted conveniently, for instance in a horizontal position extending out from the tower, this bore may be easily checked by inserting a gauge plug at the grooved end.

We would appreciate the opinion of the authors regarding the removability and accessibility of the tubes in the various mountings they have had experience with and also regarding the desirability and feasibility of periodic bore checks.

A. M. Opsahl (Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.): I note that along the 133 miles of line, there were in 1934 246 tube operations where in previous years the average line outages were about 27. From this it would appear that about 9 tubes gave indications of operation for each stroke that occurred. The multiple strokes may have struck the line at different structures and in that way have involved more than one set of tubes. Such a multiple stroke in previous years would have resulted in one outage.

The authors calculate that each tube discharging carried 10,000 to 40,000 amperes when the crest ammeters in the tower legs recorded 25,000 to 80,000 amperes. Assuming that the stroke hit the tower, such a high surge current discharging into the live conductor must necessarily result in discharges through the tubes on adjacent structures. These adjacent tubes would not necessarily pass power follow current but the surge current alone might well cause an indicator operation.

Such indicator operations due to a high surge current discharge without power follow would not be a measure of the wear and life of the tube.

Some clue as to the total number of strokes to the line possibly was found from oscillograph records, and perhaps the number of tube operations per stroke or multiple stroke was indicated by the grouping of tubes that had operated.

The 8 outages on the Glenlyn-Roanoke line were caused by 12 tubes that were found to have arced over externally. Possibly the more frequent arcovers on this line were because the insulation is some 10 to 15 per cent lower than that on the Roanoke-Danville line, requiring a much closer design of the tube.

The authors seem to imply that little other work on this type of device has been done. At the time the authors were carrying on their first series of tests, a 66 kv line 50 miles long was being equipped with "deion" flashover protectors. This protector installation, as described in detail in *Electrical World*, Jan. 19, 1935, page 48, has given a very good account of itself.

During 1931, before the line was equipped with the protectors, there were 34 outages from lightning; in 1932, before the majority of the protectors were installed, there were 26 lightning outages; in 1933 there were 3 outages with all of the protectors installed; and in 1934 there were no lightning outages on this line. There are no ground wires.

Two protectors on this line failed apparently due to excessive surge current. There have been no external flashovers of any protectors which we have in service.

V. M. Marquis (American Gas and Electric Co., New York, N. Y.): As is well known, the expulsion protective gap has a maximum and minimum 60 cycle current interrupting characteristic. It is therefore necessary in applying this tube on the transmission line to make sure that the system short circuit current does not exceed the tube rating and, unlike the situation in applying an oil circuit breaker, it is also necessary to make sure that there is at least a certain minimum short circuit current which can be fed into a line fault. Therefore, before selecting the tube ratings for both the Glenlyn-Roanoke and Roanoke-Danville lines, it was necessary to make rather careful calculations of fault currents which might exist on the system under any normal system setup.

The maximum values of short circuit current were calculated on the basis of maximum generating capacity, all grounding transformer banks, and all lines in service. The minimum values were calculated on the basis of expected minimum generat-

Table II—Interrupting Capacity Rating of Expulsion Protective Gaps

Tube Rating Amperes[1]	Number of Tubes	
	Glenlyn-Roanoke	Roanoke-Danville
400/2,000	54	903
600/2,500	450	
900/5,000	306	
Total	810	903

1. 60 cycle symmetrical effective current.

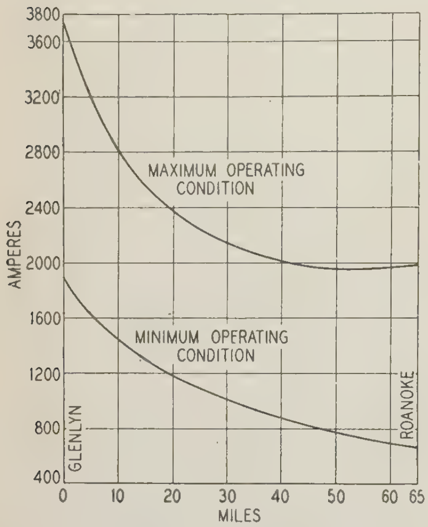


Fig. 2. Calculated system short circuit current per tube, Glenlyn-Roanoke 132 kv line

ing capacity, grounding transformer banks, and lines in service. For the maximum condition the type of fault giving the highest short circuit current and for the minimum condition the type of fault giving the minimum short circuit current were calculated. The calculated maximum and minimum currents to which the tubes might be subjected on the Glenlyn-Roanoke line are shown in figure 2 of this discussion. In this figure the upper curve represents the total current which one tube must interrupt, depending on where the tube is located on the line. The current varies from approximately 1,960 to 3,750 amperes.

The lower curve gives similar current values for one tube under conditions of minimum generating capacity on the system. These minimum currents range from about 650 to 1,900 amperes.

Since the over-all current range constitutes too great a spread for one tube, it was necessary on the Glenlyn-Roanoke line to use tubes of 2 sizes, one near the Glenlyn generating plant for a distance of approximately 25 miles out, and the other lower rated tube on the remaining 40 miles of line. On the 65 mile Roanoke-Danville line, more remote from the sources of power, it was found possible to use a tube of the same rating for the entire length.

The actual tube ratings and the number o tubes installed on each line are shown in table II of this discussion. It should be noted that the 54 low rated tubes on the Glenlyn-Roanoke line were located at the Roanoke end, and were of the 30 degree mounting type. The low rating, however, was not dictated by the short circuit characteristics of the line, but rather by a desire to obtain operating information on this lower rated tube; that is, the installation of these 54 tubes was distinctly experimental.

It is felt that the above explanation of how tube ratings were selected for these 2 lines will be of interest to those who may be considering the application of expulsion protective tubes for line protection. While it is not at present known what margin of safety there is in the tube rating, the thought immediately suggests itself that where system kilovolt ampere capacity is materially altered, it may at times be necessary to change tube ratings on lines that have tubes applied, and this of course would mean physically removing the tubes from the line and reinstalling others of a different rating. On these 2 particular lines, however, we see no immediate prospect of having to face this situation.

Multiple Lightning Strokes

Discussion of a paper by K. B. McEachron published in the December 1934 issue, pages 1633–7, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

G. D. Harding (nonmember): An analysis of the data included in table I of the paper indicates that in all probability the expulsion gap operations were the result of direct strokes to tower or ground wire and not to the lines themselves. This conclusion is based upon the results of the tests described in the paper and subsequent tests made in Pittsfield, Mass., coupled with the fact that a positive conductor was involved in the majority of discharges without regard to position on the line. The tests described show that when the tower has been raised to a high negative potential due to a direct stroke, insulator arcover should occur on the line or lines which are positive. Later tests were made at Pittsfield to determine if this were the same with a direct stroke to the line. To simulate this condition, two similar 300 kv transformers were connected with opposite polarities to 2 horizontal parallel rods spaced 36 inches apart. A metal point was suspended equidistant above the center of the rods, forming an equilateral triangle of 36 inches on a side. The point was connected to a 1,500 kv impulse generator. Provision was made to initiate the impulse generator on either the positive or negative crest of the 60 cycle wave. With a 60 cycle 60 kv effective voltage held on the rods, negative impulses (1.5×40 microsecond waves) of 680 kv crest were applied, or just sufficient voltage to arc over the gap from point to either rod. Out of 8 arcovers at this voltage 6 struck a positive rod and 2 a negative. However, when the impulse voltage was raised to 1,200 kv or 14 times the crest value of the 60 cycle wave, out of 27 arcovers only 7 struck a positive rod and 17 struck a negative rod. In the remaining 3, the discharge split and struck both conductors simultaneously. These tests show that local ionization has apparently little effect in determining which conductor is to be struck unless a definite path is established by an insulator string.

The data in the paper does not include the last record obtained with the crater lamp oscillograph, taken during a storm on September 12. This film was not available for analysis at the time the paper was prepared. The record shows a multiple stroke with 3 successive discharges having time intervals of 17 cycles and 3 cycles, respectively. The 17 cycles will change the limit of 9.5 cycles shown in figure 4 of the paper.

The accompanying table is an analysis of the record from the standpoint of polarity of phase when follow current began. The foregoing deductions are well illustrated by this oscillogram.

Discharge No.	Phase Voltage in Per Cent of Crest Value		
	1	2	3
Phase 1	−50	−98	−100
Phase 2	−50	+34*	+50*
Phase 3	+100*	+64*	+50*

* Discharge struck these phases.

W. B. Buchanan (Hydro Electric Power Commission of Ontario, Toronto, Can.): Brief reference is made to the mechanism of lightning and the necessity of understanding it thoroughly in order to predict where a stroke might make its first contact with earthed structures. Apparently the phenomenon of the stepped leader plays an important part in this mechanism and some speculation as to its cause is intriguing even if it cannot be made profitable.

The usual theoretical discussion on lightning has followed along the lines of traveling wave theory, method of images, etc., which to the average engineer seems to be a method of treatment quite dissociated from his conception of the electrodynamics of commercial circuits. What different pictures of the mechanism of lightning might be obtained by applying the idea involved in the counter electromotive force of self-induction to the path of the lightning discharge?

If $L\,di/dt$ holds true for lightning, and L while difficult to evaluate cannot be considered infinitesimal, there should be an upper limit to di/dt beyond which the counter electromotive force of self-induction opposes further advance along the former line of travel and side slip occurs. Such counter electromotive force should be very much reduced along parallel paths at say from 30 to 50 feet distant and the discharge should resume its original direction.

Such a theory might be expanded to explain how a streamer could start from the clouds directly toward a mast, then be forced to detour and take a path greater than the shortest distance. This theory also presupposes that this phenomenon occurs only on occasions when the storage of energy in the cloud is of major magnitude, and hence is observed on a comparatively small number of the total strokes. It also provides for a wide distribution of charge in an electrically charged storm cloud which in addition to providing a very heavy initial

discharge as indicated by the stepped leader recuperates rapidly and delivers a series of discharges of gradually reducing magnitude like an electric eel.

The practical value of this discussion would be to suggest that some such phenomena might be associated with contour of the country rather than with the normal electric field. An erratic contour should tend to break up clouds and limit the number of occasions when multiple strokes take place.

It would be interesting and it might be useful if the author could list such information with his records with the view to determining if under certain topographical conditions masts might be considered as giving 100 per cent protection even though in a more general way this could not be realized.

A Carrier Current Relay Installation

Discussion of a paper by O. A. Browne and W. L. Vest, Jr., published in the January 1935 issue, pages 109–15, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

E. E. George (Tennessee Electric Power Co., Chattanooga): From the maps and description of the system it is easy to understand why several of the sections could not be relayed satisfactorily by any of the conventional schemes. The worst conditions are those in which the breakers associated with the tapped station are located some distance from the point where the tap is taken from the main line. We agree that the use of some form of pilot wire protection was probably the best solution.

Some earlier schemes of carrier current pilot wire protection used considerable extra equipment in order to avoid directional relays dependent on voltage as well as current. It is our opinion that directional fault detector relays using potential, current and phase angle have been developed to the point where they are sufficiently reliable for all practical purposes. We note that no mention is made of any difficulty with the directional relays during the first 2 years of operation.

The equipment itself has an excellent operating record, since most of the difficulties with any new installation or scheme will show up during the first 2 years. Probably this good record is in part because equipment is checked daily as described. Of course, this particular arrangement is feasible only if the various substations are attended.

It is interesting to note that there have been no false operations due to system swings or out of step conditions. This indicates good coördination between operating speeds of the transmitting and tripping equipments. Probably the relay time of 8 cycles is necessary in order to secure a reasonable margin of safety. We wonder if this time could be reduced since it probably represents more than half of the overall short circuit clearing time.

From the operating experience to date, we judge that the equipment has already paid for itself in the reduced number of transmission line "burn-downs," in addition to the generally recognized advantages of improved system stability and service secured through high speed relaying.

Philip Sporn (American Gas and Electric Co., New York, N. Y.): The carrier current relaying described in the paper differs in various respects from that used on our system. The use of carrier relaying as adopted by us avoids cascading of the breakers and experiences like those involving the total interruption of the supply at the "tap-off" stations, such as Amherst, East Springfield, Cobble Mountain, Westfield, or Hampden stations.

Except for one case, in our system all stations are connected in series, and in all stations the tripping is controlled either directly or indirectly by overcurrent relays as in the sectionalizing stations of the system described in the paper. Incidentally, in the latter system the elimination of all tap-off stations would result in much faster clearing of faulty line sections in that only 2 breakers would have to operate to clear the faulty section, hence insuring simultaneous tripping of the breakers at both ends of the faulty section. With the present arrangement for faults occurring near any sectionalizing station, cascading of breakers must, of necessity, occur.

The authors state that the carrier current tripping relays are all set throughout the system to close their contacts in 8 cycles. I do not understand why such a long time is necessary. On our system all tripping relays are set for 4 cycles. Furthermore, we have just developed a new relay arrangement in which the carrier tripping relays will be set to close their contacts after 1 cycle.

An analysis of the 320 operations for the past 2 lightning seasons reported in the paper discloses that 14 per cent, namely 43, were incorrect operations. In our experience with some 30 carrier current installations on our system over the same period of time, we have not experienced one single incorrect operation that was attributable to the carrier current equipment. It would be interesting if the authors could give us some additional information on the cause or causes of these incorrect operations.

E. H. Bancker (General Electric Co., Schenectady, N. Y.): Naturally there were some unforeseen difficulties that showed up in service but the authors point out that these were all readily corrected. Because of this experience any future installations will avoid them and make performance even more perfect. However, the troubles were surprisingly few when the potential difficulties of the installation were so great. The large variation in signal vs. frequency shown in figures 8 and 9 of the paper arises from the radiating taps from which reflections may arrive in such phase relation as to greatly diminish the signal at some station. In such instances it is advisable to take frequency characteristics for each of the possible operating conditions to insure adequate signal strength at all times. In an ordinary 2 ended line, carrier equipment is located at the only 2 reflecting points and if there are any standing waves they are necessarily of such a type as to raise the signal since the line traps are a high impedance point of reflection. Under these circumstances any frequency may be selected at will without the necessity of taking line characteristic curves.

One of the important points brought out by this paper is the high order of reliability of the carrier equipment and particularly the tubes. Lack of acquaintance with such apparatus seems frequently to deter protection engineers from adopting carrier pilot and its wider acceptance should be stimulated by reports such as this which show that the carrier equipment is reliable and easily maintained. If the authors will give in their closing discussion the causes of the incorrect operations it will be seen that few, if any, of them are attributable to the carrier equipment or the scheme as a whole. The fact that exceptionally severe lightning produces many outages within an hour or 2 makes it possible for a single cause to account for a number of false operations before it is found and remedied. Thus, 18 of the total of 43 incorrect operations arose from only 2 sources (both external to the equipment) and ordinarily would have occasioned only 4 or 5 wrong operations if several more faults had not followed in rapid succession each time. Taking these facts into consideration, the performance record will be seen to conform with accepted good practice while giving faster relaying than could otherwise be obtainable.

Carrier pilot relaying does give fast, selective, and reliable protection to simple or complicated systems, thereby permitting the greatest latitude in system design and operation. Its use saves relay short circuit studies, minimizes damage at the fault, reduces customer complaints, and increases revenue.

H. D. Braley (New York Edison Co., New York, N. Y.): The paper is of particular interest in that the reasons for the choice of the equipment are stated and the operating difficulties are frankly discussed. A further discussion of these phases would be of material value to others having similar problems.

It is stated that one of the chief drawbacks incident to the use of other types of relay equipment was the long time delay in clearing line sections because high current and long time settings were required for normal operation. Is it to be inferred from this that these settings were required to prevent tripping the lines from surging, or were these requirements essential for maintaining selectivity?

Among the advantages mentioned for the carrier current type of control it is stated that no extensive calculations are required. While this argument has been advanced before with respect to the advent of other new relay developments, we have not as yet found any of them, including carrier current control, to justify omitting extensive fault analysis studies. There is probably no system in which the fault current does not vary between wide limits with changes in system capacity and switching arrangements. Both of these factors affect materially the magnitude of fault currents

and their distribution in the high tension network. This variation of course establishes limits for both time and current settings even when the relays are controlled by carrier current.

Referring to the type of relay equipment used, it is noted that the type *IDP* directional relay is used for tripping at the tap stations instead of the type *IAC* overcurrent relay. Explanation of the reason for this would be helpful.

It would appear from figure 5 that no provisions were made for clearing bus faults. If protection was provided for this purpose, the scheme employed, its operating speed, and the type of back-up protection used to protect against breaker and relay failure would be of interest.

The data given in tables I and II are very interesting indeed since they are a direct measure of the effectiveness of the equipment. A detailed analysis of the 8 causes of incorrect operation found would be a valuable addition to the paper. Referring to table II it is rather surprising to find that such a large percentage of the lightning faults still involved both circuits after installation of the faster relaying. Possibly details of the line construction, such as use of ground wires, conductor spacing, insulation level employed, etc., would throw further light on this point.

The beneficial results of faster relay protection in maintaining stability during system trouble cannot be questioned. This is well brought out in the paper by the statement that thus far no trip-outs have resulted from surging. It would be of interest to compare the present operating experience with that which was had previously. I should also like to ask the authors if any special provisions were made for controlling the point of separation, under out-of-step operation.

W. A. Lewis (Westinghouse Elec. and Mfg. Co., E. Pittsburgh, Pa.): The development of carrier current relaying equipment is a logical step in improving system protection. Balanced line and distance relay types of protection are capable of extremely fast fault clearing in many cases, but must employ a time delay in the final clearing of faults near one bus. With simple uniform circuit arrangements, without taps, the time delay required may be kept to the order of one breaker operating time (plus margin), and this usually may be tolerated, unless the system is operating close to its power limits. However, complex circuit arrangements, such as tapped lines, wide differences in length of associated circuits, and other causes often render much greater time delay necessary before the fault can be finally cleared. Carrier current relaying, although expensive, reduces the time delay required for selectivity from the time of breaker operation down to the time required for a relay to transmit a carrier signal, and, as a result, the average time of fault clearing may be appreciably reduced. Thus this form of protection may be expected to find a definite place on important lines throughout the country.

Although many of the lines discussed in the paper are tapped, and satisfactory protection is evidently being obtained, it does not follow that carrier current protection of the form described may be applied indiscriminately to give protection for tapped lines under all operating conditions. The principle of operation is that power flow toward a bus during a fault will transmit a carrier signal which prevents tripping of all of the breakers feeding the line section. If this can occur at one of the terminals of a faulted line section, proper tripping will be prevented. It is possible for this condition to be realized on some of the lines shown in figure 2 of the paper, for example, one of the lines between Cabot station and Chicopee, with a tap to East Springfield. Let us assume that a fault occurs on the right hand line near Cabot station and that before the fault the breaker on the left hand line at Chicopee is open. Then the fault current from Chicopee will flow over the faulted line to the point of tap, and will then divide, part going along the faulted line to the fault and the remainder passing over the tap, into the bus at Springfield, then out from Springfield into the sound line, over the sound line to the Cabot bus and then back to the fault through the faulted line from Cabot. The flow of power on the faulted line into the bus at Springfield is in the direction to cause transmission of carrier and block tripping. It is, of course, recognized that the operating condition is abnormal, but it should not be overlooked in the application of the relay system. In some cases, if the stations fed by the taps are interconnected with other stations, conditions such as described may arise with normal operating connections. The relaying of tapped lines, difficult at best, may be made easier by carrier current equipment, but each case must be investigated to make sure improper blocking will not occur, or, if it does, that the conditions and consequences are recognized.

In the paper, page 114, the long life of the type 10 tubes is attributed to the fact that the flow of plate current is intermittent. Our experience with a similar type of tube having an oxide coated filament indicates that the flow of plate current does not decrease the life of that type of tube appreciably, if the tube is conservatively applied, so that continuous plate current may be employed if desired. A system of carrier current protection using continuous carrier current, except at time of fault in the faulted section, has been designed and tested and is now being placed in service. This system has the advantages that faster operation is possible, and that an automatic indication of carrier failure is immediately given, rendering frequent checking unnecessary. The small additional amount of energy drawn by the plate circuit is negligible in most cases.

O. C. Traver (General Electric Co., Philadelphia, Pa.): The authors have given us some very interesting and valuable facts, cold facts. Table I is particularly chilly. A correct performance of 86.6 per cent would seem to leave much room for improvement but fortunately that's not the picture when the remaining facts are assembled. There must be other grounds for the authors' last sentence, which states "This installation of relay equipment has operated in an entirely satisfactory manner and has justified its cost in the results so far obtained."

Reading elsewhere we find that all causes for incorrect action have been corrected excepting for only 2 operations, which out of a total of 98 line sections in trouble during the 2 year period would indicate that one might predict a possible 98 per cent performance for the future. You may suggest that other forms of trouble may develop and that 98 per cent is therefore too optimistic. We can just as well hope that the 2 original unknown causes will have been solved and the percentage therefore raised.

I think we can say that tapped lines have been protection engineers' enemy number 1. Then keeping in mind that all these line sections were tapped you will understand why I suggest that carrier current pilot protection stands alone for this class of circuit.

No special provisions were made in these equipments for operating under oscillating conditions. It is therefore gratifying to see that the performance has been satisfactory in this regard. I am glad to tell you that equipment is now available to actually go through a definitely out-of-step condition and not trip when its own line is sound but still clear if an internal fault develops.

May I also announce that in keeping with the development of 3 cycle oil circuit breakers, carrier protection has more recently been supplied which functions in 2 cycles. And the limit in speed is not yet in sight.

Looking at the data from another angle we are struck by the statement that of 79 line sections tripping out due to lightning only one could not be immediately returned to service. What an argument this appears to be for automatic reclosing.

Vibration Analysis—Transmission Line Conductors

Discussion of a paper by W. B. Buchanan published in the November 1934 issue, pages 1478–85, and presented for oral discussion at the general overhead line problems session of the winter convention, New York, N. Y., January 23, 1935.

E. Bate (nonmember): The paper opens with an argument for the validity of the method of analysis of dampers and other features of antivibration design of transmission lines using traveling waves instead of standing waves. This approach to accurate evaluation and comparison of certain features is reasonable when it is remembered that, in the process of establishing a response of resonant nature to wind eddies on a conductor, a period of transmission and reflection of traveling impulses must occur, and, if during this period sufficient absorption and attenuation of the eddy induced impulses can be caused, there will be little chance of resonance being achieved.

The methods described are all the more valuable since there is great difficulty in producing and controlling wind induced eddies on a transmission span, and it is essential to accurate study that the conditions of the experiments shall be under complete control.

Of the details of the methods and apparatus, I would particularly wish to know whether the curvature recorder is able to measure curvature of the conductor so close to the fixed clamp as to give an accurate indication of flexure stresses at the nose of the clamp. Judging from figure 3, the recorder, as there indicated, would be measuring the average curvature between the clamp nose and the point of attachment of the instrument some distance therefrom. My impression is that there is a very rapid change of curvature close to the clamp, and that to obtain satisfactory measurements of the curvature very close to the clamp, a special arrangement of apparatus will be necessary. These remarks are based, of course, solely on the examination of figure 3, and the author might quite satisfactorily dispose of the suggestion that the curvature actually measured is not the critical quantity.

In a paper to the Institution of Engineers, Australia, in August 1930, the writer described a crude attempt to measure curvature near the clamp, in comparison with curvature in the span, and obtained a ratio of the former to the latter somewhat in excess of that quoted by Buchanan. A further examination of this point would be of great interest to those studying the fatigue of transmission conductors.

The apparatus for measurement of curvature might yield satisfactory results, as far as determination of critical curvatures close to the clamp is concerned, if the experiments were more on a single span of cable of any desired loop length, mechanically oscillated, with the curvature recorder so mounted as to give the closest possible approach to the mouth of the clamp. By recording curvature and displacement at a number of positions, curves could be obtained, extrapolation from which would enable a close approximation to be made to the critical curvature.

Having measured the curvature, the determination of stress is dependent on some assumptions as to stiffness at the point of fracture, clamping stresses, and other quantities, of which in the case of a stranded conductor our knowledge is very vague.

When dealing with the measurement of reflection and attenuation as functions of the clamp, cable, and damper arrangements, the author has translated into measurements with a convincing degree of precision, measurements of a cruder nature which have no doubt been made elsewhere. For instance, in 1929 the writer, in studying the effect of a particular damper, used a test which was then called the "bump" test, in which dampered and undampered arrangements were compared by timing and counting reflections at various points in the span, the "bump" being produced in a carefully practiced manner. These tests, which were then looked upon as generally corroborative of other visual tests and graphic records of the absorptive effect of the damper, gave, in fact, for an underhung or "festoon" damper similar results to those quoted by Buchanan.

This part of the recording work being carried out by the author is of great interest and value, because of the precision of the records, and the author's evident intention to pursue these investigations over the many conductors of the Hydro Electric Power Commission. When correlated with experience in the field, the investigations should be fruitful in an advance of both knowledge and practice.

The writer would like to suggest that the virtue of any damper arrangement may rest not only in its absorptive effect, but also in its ability to provide reflections which by their phase interference mechanically prevent progress to a resonant condition, that is, are dissonance producing. This effect was observed in the above mentioned "bump" applied to transmission spans. In the undampered span, 900 feet long, conductor 37-strand A.C.S.R. ($^1/_8$ inch strands), the original impulse would persist, traveling to and fro almost unchanged in shape for about 85 seconds, but in the span provided with an underhung damper the impulse was so broken up within a few seconds that slight wave motion appeared to exist throughout the span, and within 50 seconds the cable was quite still.

G. W. Stickley (Aluminum Company of America, Massena, N. Y.) and **R. G. Sturm** (nonmember): Before discussing the testing procedure and the results obtained therefrom as presented by the author, let us first look carefully at the nature of resonant vibrations in conductors at frequencies set up by the wind, and then look at the normal natural frequencies of vibration of a cable.

A great deal of work has been done which shows conclusively that when a uniform fluid stream passes over a cylinder, eddy currents are set up on the leeward side. These eddies have been found to oscillate regularly, whirling first one way and then the other. It has also been shown that the frequencies of these oscillations are dependent upon the diameter of the cylinder and the velocity of the fluid stream. The frequency of the eddy currents set up at a transmission line conductor when a uniform wind is blowing will all tend to be in the neighborhood of some average value depending upon the mean velocity of the wind and the diameter of the cable. It is known that the wind always varies slightly from time to time, and even at the same time, throughout a normal span. Also, due to stranding, the effective diameter of the cross section of any cable varies from point to point over such a distance, although such variations may only be of the order of a few thousandths of an inch. In view of these variations one might expect the frequency of the eddy currents to vary slightly from the average at various points along the cable, such that the phase of oscillation of the eddy currents may be slightly different for some instant at 2 points along the cable only a relatively short distance apart.

Now let us consider the natural vibration of a cable. From the principles of mechanics it can be shown that a cable may vibrate in any one of a number of forms, *e. g.*, it might vibrate in one single loop, 10 loops, or 100 loops, depending upon the frequencies at which it is agitated. The source of these agitations might be of any nature whatever, but the cable will settle down to a mode of vibration such that its natural frequency in that particular mode of vibration will most nearly agree with the frequency of the agitating forces.

The cable will always vibrate with a frequency such that there will be a whole number of loops in the span, except for very minor effects of the flexural rigidity of the cable at the ends of the span.

As described above, eddy currents are set up when a wind is blowing over the cable. These eddy currents exert minute forces on the cable, and when an average frequency of these eddy currents corresponds to a natural frequency of vibration of the cable at which a whole number of loops may be formed, harmonic vibration is possible. Because of the above mentioned variations these forces will tend to displace the cable slightly, tending to cause it to oscillate at the same frequency as the eddy currents, which will cause loops to form independent of the location of these variations along the span. If the wind varies slightly, the frequency of applied forces will vary slightly, with the result that perfect resonance is probably maintained only momentarily and the cable will assume the best average frequency of vibration. The amplitude of vibration will gradually build up and will reach a magnitude which is limited either by the variations in wind velocity and the cable diameter or by the dissipation of energy by the cable and any attachments. Thus we have vibration of transmission line conductors reaching a state of harmonic vibration without the necessity of imagining the cable struck at 2 points causing traveling waves, which in turn excite the cable to vibration.

Because of the partial flexibility of the clamps supporting the cable, and because of harmonics with vibration set up in adjacent spans or in the towers, there are sudden impulses received by the cable from the clamps *after* it has started to vibrate. Since cable spans in which nothing is in contact with the cable, except the clamps, do vibrate and do appear to have traveling waves in addition to standing waves, it would seem that the nature of the development of vibration just explained is the only one that is tenable. Therefore, the behavior of the cable in service can only be approximated by artificially plucking the cable and sending a series of traveling waves through the span. If these waves are set up at frequencies which will cause the cable to vibrate in a normal number of loops, the approximation may be close, provided excessive energy is not put into the cable, but if the waves are intermittent or relatively infrequent, such that the cable does not vibrate normally in a number of loops, the results obtained may be subject to considerable doubt.

From experience we have found that very misleading conclusions can be drawn from tests in which vibration is more or less closely approximated by artificial means. It is for this reason that in addition to our laboratory testing we have found it essential to make tests on full size spans of conductors in which all vibration is caused naturally by the wind.

The author refers to direct measure of the stresses in the cable and obviously by these stresses he refers to the increase in tension resulting from the increased length of the cable around the loops. The magnitudes of tension set up in this manner are very small for all amplitudes encountered in transmission lines, especially in comparison with the bending stresses.

News

Of Institute and Related Activities

Plans for the South West District Meeting and Student Branch Convention

THE meeting of the South West District of the A.I.E.E. will be held at Oklahoma City, Okla., from Wednesday to Friday, April 24–26, 1935. The convention of the student Branches of the South West District will be conducted jointly with this meeting on April 25 and 26. Headquarters will be at the Skirvin Hotel, where all the technical sessions will be held. The 14th floor, known as the Skirvin Roof, will be retained exclusively for the use of the meetings during the 3 days; the technical sessions will be held in the Venetian Room and the student sessions will be held in the Rose Room. An attractive program consisting of 5 technical sessions, inspection trips, dinner and dance, and a golf tournament has been arranged by the committee. A special entertainment feature has been planned for the visiting women.

Oklahoma City, located at the heart of the area comprising the South West District of the Institute, is a city of over 200,000 population. Its development has been rapid. On the morning of April 22, 1889, the site of Oklahoma City was prairie land with low curving hills, covered with high grass and with bunches of thick timber along its river banks. At noon of this historic day the territory was officially opened and thousands of eager men and women made "The Run" from the border into a country never before opened to white settlement. At evening, 6,000 pioneers from the 4 points of the compass gathered around their campfires; a city had come into being between the rising and setting of the sun. From that time on, Oklahoma City's growth has been phenomenal until now, 45 years later, it has become a thriving center of trade, industry, and education.

Oklahoma City possesses splendid transportational facilities radiating in all directions. Six trunk line railroads, interurban lines in 3 directions, 60 trucking lines, 102 daily passenger bus schedules, and 5 air line routes operate in and out of the city. Six Federal designated highways converge in the city from 10 directions.

The city is in the center of the mid-continent oil fields. From hotel or office window is available a panoramic view of one of the richest and most phenomenal oil pools in the last decade, located on the city's very doorstep. Also, 19 of the 22 major agricultural crops of the nation are produced on a commercial scale within the city's immediate trade territory. These conditions have given rise to the city's important industries, including oil and gas production and refineries; oil field supplies; steel and iron works; packing plants and livestock market; flour and grist mills; cotton gins and compresses.

Including its own Oklahoma City university, there are within a radius of 75 miles of Oklahoma City institutions of higher learning having enrolled 73 per cent of the college students of the state. Among the many points of interest to Oklahoma City visitors are the Oklahoma State Capitol, the State Historical and Indian Museum, Oklahoma City University, Lincoln Park and zoo, Packingtown and stockyards, and Oklahoma City oil fields.

Oklahoma City and the surrounding territory is served by the stations and transmission lines of the Oklahoma Gas and Electric Company, whose facilities supply most of the entire central and northwest parts of the state. The Public Service Company of Oklahoma serves the northeast section and the Southwestern Light and Power Company the southwest portion of the state. The southeastern section is served mainly by the Central States Power Company.

Entertainment Features

No special arrangements are being made for dinner on the first day of the meeting so that members may be free to look up acquaintances and dine with them. The afternoon of Thursday will be given over to general sports and inspection trips. A luncheon-bridge has been arranged for the women, and a men's golf tournament will be held in the afternoon. The usual dinner, followed by dancing and bridge, will be the feature of Thursday evening. No special entertainment has been planned for Friday and Saturday, but the committee will be glad to arrange for golf matches, further inspection trips, informal meetings, or any other activities desired by the visitors.

Women's Entertainment

The women visiting during the convention are assured of a pleasant time. On Thursday afternoon a luncheon-bridge has been arranged for their entertainment at the Oklahoma City Golf and Country Club, in addition to the main social events on the program. Trips to points of interest in and around Oklahoma City will be arranged by the committee.

Golf

On Thursday afternoon, April 25, at 1:30, there will be a golf tournament at the Oklahoma City Golf and Country Club. Two suitable prizes will be awarded, the basis to be determined by the golf committee. No entrance or green fees will be charged registered members of the Institute for this tournament.

Arrangements have been made with both the Oklahoma City Golf and Country Club and the Twin Hills Golf Club for visiting delegates to play either course on any day of the convention, upon payment of $1 green fee. Both of these courses are of championship caliber and are interesting tests of golf. The Oklahoma City Golf and Country Club was the scene of the Trans-Mississippi Tournament in 1933. The Twin Hills Golf Club was the scene of the Western Amateur Tournament in 1934, and the National P. G. A. Tournament will be held at Twin Hills during 1935. Also, there are a number of public courses available to delegates. Lincoln Park (municipal) has 2 complete 18 hole grass green courses.

Also, tennis facilities are available to those who prefer this form of recreation.

Inspection Trips

Four inspection trips are scheduled, starting at 1:30 Thursday afternoon. One of these trips will cover many interesting features of the Oklahoma City oil field, including drilling, pumping, and refining operations. A photograph showing one view of this oil field was reproduced in ELECTRICAL ENGINEERING for February 1935, page 205. A second inspection party will visit points of interest on the Oklahoma City system of the Oklahoma Gas and Electric Company, including the Arthur S. Huey memorial generating station, the office of the chief dispatcher, and the short-circuit calculating board of the Company's transmission system. The Reno Street substation of this system was illustrated in ELECTRICAL ENGINEERING for February 1935, page 250.

A third group will visit the 34 story First National Bank Building, the plants of the Southwestern Bell Telephone Company and the Oklahoma Publishing Company, a broadcasting studio, an air conditioning installation, and other interesting places. A fourth party will visit the University of Oklahoma at Norman, 18 miles south of Oklahoma City. One of the most outstanding departments of its engineering school is that of petroleum engineering, whose laboratory contains a complete oil refinery.

Convention Dinner

The dinner will be held Thursday evening at 7:00 o'clock in the beautiful Venetian Room of the Skirvin Hotel. Tickets are $1.50 per plate. Music and novelty entertainment features will be provided during the dinner.

Following the dinner there will be dancing in the Venetian Room, with music provided by Spencer's Orchestra, until 12:00 midnight. Provisions will be made for both auction and contract bridge at tables convenient to the dance floor for those who prefer this form of recreation, or wish to alternate bridge and dancing. Attractive bridge prizes will be offered. The evening will be informal.

Registration

All who plan to attend this meeting are urged to register in advance by mail, if possible, by writing to E. B. Jennings, Southwestern Bell Telephone Company, Oklahoma City, Okla. Members should complete their registration after arrival so as not to miss the opening session. There will be no registration fee.

Hotel reservations should be made directly with the hotel preferred. The rates of the headquarters hotel and other leading hotels are given in table I.

An information desk will be open each day on the 14th floor of the Skirvin Hotel and a bulletin board for notices will be provided for the convenience of the members.

Table I—Hotel Rates

Hotel	Single	Double
Skirvin* (headquarters)	$2.50, 3.00	$3.00, 3.50, 4.00
Biltmore	$2.50, 3.00, 3.50, 4.00	$4.00, 5.00, 6.00
Black	$2.00, 2.50, 3.00	$3.00, 3.50, 4.00
Wells-Roberts	$2.00, 2.50, 3.00	$3.00, 3.50, 4.00
Huckins	$2.00, 2.50	$3.00, 3.50
Kinkaid	$1.25, 2.50	$2.00, 3.50

All of the foregoing rates are with bath or shower.
* Special rates at headquarters hotel for students only: 4 to 6 in room with bath, $1 per person.

Ample parking facilities have been arranged at the Auto Hotel, 112 West First Street, located conveniently to the Skirvin Hotel, for $0.50 per day with in-and-out privileges and with delivery and pick-up service at the hotel.

Technical Program

The papers committee has arranged in so far as possible a broad program which should be of interest to many members. Some of the papers scheduled were selected expressly to bring out in the discussion the latest trends in new developments and operating practice. For example, the paper on the "Use of Instantaneous Overcurrent Relay for Distance Relays" should bring out in the discussion other comparable methods of relaying which may be applicable to the type of power systems that exist in the South West District.

The papers in the insulation and protection session will afford opportunity for discussions of this topic from the standpoint of both telephone and power system equipment. Another paper on "Recommended Transformer Standards," presented at the Institute's 1935 winter convention, has been rescheduled to give engineers from this District an opportunity to discuss the proposed standards. This paper and the one on "Protective Devices for Substations and Their Relation to Insulation Strength" will provide a basis for discussing the questions of insulation coördination, insulation strength, and protective devices.

In the same way rescheduling of the paper entitled "Portable Schering Bridge for Field Tests" will present an opportunity for a broader and more recent discussion of field testing of insulation by other methods.

In another session 2 papers on metering will present the present trends in metering practices with particular reference to outdoor meters. The discussion should bring out a suggested method for evaluating the factors to be considered in determining the extent to which it is economical to go in modernizing present metering installations. Another paper on "Prevention of Cable Sheath Corrosion" is of interest to both power and communication engineers. It describes a method of mitigating soil corrosion of cable sheath by means of applying counterpotentials. Still another on "Step Type Feeder Voltage Regulators" offers an opportunity for an expression of opinion in discussion as to the size and number of steps most desirable in this type of regulator.

The distribution and transmission session will be devoted principally to design and operation of distribution systems. One of the papers will show the economies that can be effected by the use of supplementary regulating devices, not only for compensating of the normal drop in voltage in distribution systems but also for reducing abnormal fluctuations in voltage which result from the use of large appliance motors in residential districts. The discussion of this paper with that of another on circuit interrupting and reclosing devices should also advance other principles or practices which have a bearing on the economical design and operation of distribution systems.

The symposium on engineering education will consist of discussions based upon the various papers which have been published on this subject in Electrical Engineering during the past 2 years.

The oral discussion of these papers at the meeting in the foregoing manner is desirable but only discussion which is pertinent to the papers which have been published in advance will be acceptable for consideration for publication. Rules governing discussions of both unpublished papers and published papers are given in the paragraphs immediately after the following list of papers tentatively scheduled for presentation. For all papers in this list which have been published in Electrical Engineering, reference is given to the issue and page.

Tentative Program

Wednesday, April 24

9:00 a.m.—Registration—Venetian Room, 14th floor

9:30 a.m.—Opening of Meeting—Venetian Room, 14th floor

Presiding: F. J. Meyer, vice president, South West District, A.I.E.E.

General Technical Session

Presiding: R. F. Danner and H. R. Fritz

Use of Instantaneous Overcurrent Relay for Distance Relays, C. H. Frier, Oklahoma Gas and Electric Co.

* Electrical Engineering in Geophysical Exploration, L. J. Neuman, Houston, Texas.

A Power Company Communication System, E. E. George, Tennessee Electric Power Co., and O. J. Huie, Southern Bell Telephone and Telegraph Co. March issue, p. 262–5

12:15 p.m.—Luncheon Meeting of the District Executive Committee

2:00 p.m.—Insulation and Protection Session—Venetian Room, 14th floor

Presiding: Ralph Pittman and L. C. Starbird

* Telephone Protection, A. T. Campbell, Southwestern Bell Telephone Co.

Skirvin Hotel in Oklahoma City, Okla., which will be the headquarters for the Institute's South West District meeting, April 24–26, 1935

* PROTECTIVE DEVICES FOR SUBSTATIONS AND THEIR RELATION TO INSULATION STRENGTH, A. M. Opsahl, Westinghouse Electric and Mfg. Co.

RECOMMENDED TRANSFORMER STANDARDS, H. V. Putman, Westinghouse Electric and Mfg. Co., and J. E. Clem, General Electric Co.

Dec. 1934 issue, p. 1594–7

PORTABLE SCHERING BRIDGE FOR FIELD TESTS, C. F. Hill, T. R. Watts, and G. A. Burr, Westinghouse Electric and Mfg. Co.

Jan. 1934 issue, p. 176–82

Thursday, April 25

9:00 a.m.—Student Technical Session—Rose Room, 14th floor

9:00 a.m.—General Technical Session—Venetian Room, 14th floor

Presiding: C. I. Hendricks and R. W. Linney

* PRESENT TRENDS IN METERING PRACTICES, H. P. Sparkes, Westinghouse Electric and Mfg. Co.

* ECONOMICS AND ENGINEERING OF NEW METERING METHODS AND EQUIPMENT, R. G. Meyer and, Union Electric Light and Power Co.

CAUSES AND MITIGATION OF CABLE SHEATH CORROSION, J. B. Blomberg and Norvel Douglas, Southwestern Bell Telephone Co.

12:15 p.m.—Luncheon Meeting of Committee on Student Activities

Chairman, Professor J. A. Correll

1:30 p.m.—Assemble for Inspection Trip

7:00 p.m.—Dinner—Venetian Room, Hotel Skirvin

9:00 p.m.—Dancing and Bridge—Venetian Room, Hotel Skirvin

Friday, April 26

9:00 a.m.—Student Technical Session—Rose Room, 14th floor

9:00 a.m.—Distribution and Transmission Session —Venetian Room, 14th floor

Presiding: Stanley Stokes

* ECONOMICS AND APPLICATION OF SUPPLEMENTARY REGULATING DEVICES FOR DISTRIBUTION CIRCUITS, P. E. Benner, General Electric Co.

* CIRCUIT INTERRUPTING AND CIRCUIT RECLOSING DEVICES FOR DISTRIBUTION SYSTEMS, D. C. Prince, General Electric Co.

STEP TYPE FEEDER VOLTAGE REGULATORS, L. H. Hill, Allis-Chalmers Mfg. Co.

Feb. 1935 issue, p. 154–8

2:00 p.m.—General Session—Venetian Room, 14th floor

Presiding: M. C. Hughes

Demonstration lecture: VACUUM AND GAS FILLED TUBES AND THEIR APPLICATION IN THE POWER INDUSTRY—D-C TRANSMISSION, C. W. Stone, General Electric Co.

SYMPOSIUM ON ENGINEERING EDUCATION—Discussers: J. B. Thomas, Texas Electric Service Co.; T. F. McMains, Western Union Telegraph Co.; F. C. Bolton, Texas A. and M. College; B. D. Hull, Southwestern Bell Telephone Co., and I. H. Lovett, Missouri School of Mines and Metallurgy

* These papers will be presented and discussed at the meeting but they have not been accepted for publication and neither the papers nor the discussion based upon them will be published.

RULES FOR PRESENTING AND DISCUSSING PAPERS

In general, the time allowed for the presentation of each paper should not exceed 15 minutes unless otherwise arranged with the chairman of the program committee, R. F. Danner, care of Oklahoma Gas and Electric Company, Oklahoma City, Okla., or unless the presiding officer meets with the authors preceding the session to arrange the order of presentation and allotment of time for papers and discussion. Each speaker unannounced by the presiding officer is to step to the front of the room and announce, so that all may hear, his name and professional affiliation.

Discussion of Unpublished Papers. Those wishing to discuss any of the unpublished papers should write to R. F. Danner (at the above address) for mimeographed copies. It is suggested that discussers be limited to 10 minutes each and preference will be given to those who have sent copies in advance to R. F. Danner, chairman of the program committee. After these discussions have been given, the meeting will be opened for general discussion. The discussions of the unpublished papers will not be considered for publication.

Discussion of Published Papers. The same procedure governing the presentation of discussions of published papers should be followed as for the unpublished papers except that the *written* discussion to be submitted for consideration of publication should not be longer than the equivalent of 5 minutes' reading time. Discussion to be considered for publication should be based only upon the published papers and it must be submitted in triplicate (one of these copies to be the original, typed double spaced) to C. S. Rich, secretary of the technical program committee, A.I.E.E. headquarters, 33 West 39th St., New York, N. Y., on or before May 10, 1935. Discussion received after this date will not be accepted.

COMMITTEES

The committees handling the work in connection with the Oklahoma City meeting are:

General Convention Committee—F. J. Meyer, vice president, District 7; C. W. Mier, secretary, District 7; A. Naeter, *chairman*, Oklahoma City Section; C. E. Bathe, secretary, Oklahoma City Section; and the chairmen of the 6 committees which follow.

Papers Committee—R. F. Danner, *chairman*, D. D. Clarke, C. I. Hendricks, H. R. Fritz, R. J. Foley, J. A. Correll, M. C. Hughes, G. N. Pingree, M. B. Wyman, and R. R. Pittman.

Attendance and Publicity Committee—W. A. Kitchen, *chairman*, Roscoe Schaffer, J. S. Wantland, G. A. Dyer, A. L. Maillard, C. H. Kraft, E. G. Conroy, and J. B. Burr.

Transportation and Trips Committee—E. D. Freeman, *chairman*, G. E. Larason, R. W. Coursey, C. H. Frier, S. H. Lyons, T. E. Cutler, J. W. Shawver, W. H. Stueve, and E. T. Harrison.

Reception and Registration Committee—E. B. Jennings, *chairman*, Roy Jones, C. E. Musson, J. D. Browder, Leo Valentine, R. G. Brown, J. S. Wantland, Leonard King, E. E. Miller, Chris Heffner, W. A. Murray, Carl Almquist, and E. C. Fisher.

Finance Committee—F. B. Hathaway, *chairman*, C. E. Bathe, and W. M. Groves, Jr.

Entertainment and Arrangements Committee—A. C. Bookout, *chairman:* Hotel and Convention Hall Arrangements, E. H. Dinwiddie, *chairman*, John Wallis, J. S. Porter, and B. McDermott; Banquet, Ralph Randall, *chairman*, Roscoe Schaffer, and J. S. Joseph; Dance, C. M. Mackey, *chairman*, D. J. Mahaney, and J. W. Shawver; Bridge, W. A. Murray, *chairman*, L. B. Bass, and E. G. Green; Women's Luncheon-Bridge, C. L. Jobe, *chairman*, J. P. White, and S. H. Lyons; Women's Entertainment, Mrs. F. J. Meyer, *chairman;* Golf, O. K. Morell, *chairman*, Leo Valentine, and J. B. Kibler; Student Entertainment, R. W. Coursey, *chairman*, R. L. Jones, and E. T. Harrison.

Future AIEE Meetings

South West District Meeting,
Oklahoma City, Okla., Apr. 24–26, 1935

Summer Convention,
Ithaca, N. Y., June 24–28, 1935

Pacific Coast Convention,
Seattle, Wash., Aug. 27–30, 1935

Great Lakes District Meeting,
Indianapolis—Lafayette Section territory, Oct. 24–25, 1935

Winter Convention,
New York, N. Y., Jan. 28–31, 1936

North Eastern District Meeting,
New Haven, Conn., May 1936

Summer Convention,
Los Angeles, Calif., June 22–26, 1936

Middle Eastern District Meeting,
Akron, Ohio (date to be determined)

Counselors and Branch Chairmen of District 2 Meet

A meeting of the committee on Student activities of the Institute's Middle Eastern District, number 2, and of the student Branch chairmen of that District was held at Pittsburgh, Pa., January 8, 1935. The morning was devoted to an inspection trip with a luncheon at noon, and the Pittsburgh Section meeting was attended in the evening. During the afternoon separate meetings were held by the committee on Student activities and by the Branch chairmen.

CONFERENCE OF COMMITTEE ON STUDENT ACTIVITIES

The committee on Student activities consists of the District vice president and secretary, and all student Branch counselors in the District. The following student Branch counselors were present at the conference:

J. T. Walther, University of Akron, Ohio
G. A. Irland, Bucknell University, Lewisburg, Pa.
G. McC. Porter, Carnegie Institute of Technology, Pittsburgh, Pa.
H. B. Dates, Case School of Applied Science, Cleveland, Ohio
T. J. MacKavanagh, Catholic University of America, Washington, D. C.
A. G. Ennis, George Washington University, Washington, D. C.
H. E. Dyche, University of Pittsburgh, Pa.
H. S. Bueche, Villanova College, Villanova, Pa.
A. H. Forman, West Virginia University, Morgantown

In addition to the above, Prof. A. M. Wilson of the University of Cincinnati, Ohio, and vice president from Institute's Middle Eastern District, and Dr. C. F. Scott, professor emeritus, of electrical engineering Yale University, New Haven, Conn., were present.

At this conference, the following action was taken "Resolved that it is the sense of this meeting that there shall be an annual combined meeting of the counselors and Branch chairmen, preferably in the early fall. Resolved that the next meeting be held in the early fall of 1935." It

was also stated that many counselors preferred that when the annual meetings of the Middle Eastern District are resumed, the Branch conference be held at the same time and place.

The advantages of electing student officers early in the fall was discussed. The importance of choosing good student officers was pointed out, and the advantages of daytime meetings of the student Branches also were discussed.

The history of the committee on Student activities in this District was reviewed, and opinions were expressed on possible modifications of the present form of organization. It was resolved that a chairman be elected annually at the time of the annual counselors conference, and that there be no other elected officers. It was also resolved that the incoming chairman be instructed to appoint an advisory committee, consisting of the retiring chairman and 3 other counselors, although the chairman "shall be held responsible to the counselors of the District for the efficient promotion and organization of conferences and meetings of counselors and student chairmen." The power was given to the chairman of designating to other counselors such duties as he might deem necessary.

Prof. A. H. Forman, head of the department of electrical engineering of West Virginia University, Morgantown, was elected chairman of the Branch counselors of the District. He assumed office immediately.

Conference of Branch Chairmen

At the conference of the student Branch chairmen, methods for improving the effectiveness of A.I.E.E. Branches in the District were discussed in considerable detail, and many valuable suggestions were introduced. This conference afforded an opportunity for an effective exchange of ideas among the different Branches.

Sixteen of the 20 student chairmen in the District attended. Those present were:

W. Auvil, University of Akron, Ohio
C. A. Beers, Case School of Applied Science, Cleveland, Ohio
W. E. Schuyler, Jr., Catholic University of America, Washington, D. C.
W. C. Keiber, Jr., Lafayette College, Easton, Pa.
T. M. Gluyas, Jr., Pennsylvania State College, State College
F. L. Musselman, University of Pennsylvania, Philadelphia
C. A. Motz, George Washington University, Washington, D. C.
C. B. Jacobs, Ohio Northern University, Ada
C. R. Hope, Ohio State University, Columbus
R. C. Woltz, Ohio University, Athens
J. A. Klekotka, Villanova College, Villanova, Pa.
J. W. Kyle, West Virginia University, Morgantown
A. J. Hornfeck, University of Pittsburgh, Pa.
F. W. Francis, Bucknell University, Lewisburg, Pa.
H. B. Coleman, Drexel Institute, Philadelphia, Pa.
H. J. Corning, Carnegie Institute of Technology, Pittsburgh, Pa.

Innovations Being Planned for the Summer Convention

The development of the program for the 51st annual summer convention of the Institute, to be held on the campus of Cornell University, Ithaca, N. Y., June 24–28, 1935, is progressing rapidly. Advantage will be taken of the splendid facilities which the university offers in the way of meeting halls and modern dormitory accommodations to present an enlarged program at moderate cost to those who will be in attendance.

Already 10 technical sessions have been tentatively scheduled in 9 distinctly different fields of activity. Each of these sessions embraces several papers which will present the latest theories and practices in the following fields: protective devices, instruments and measurements, electrical machinery (2 sessions), education, communication, applications to iron and steel production, electrochemistry and electrometallurgy, power generation, and power transmission. Some of the papers for the protective devices session have been published already in the February issue of Electrical Engineering. They deal with circuit breaker performances, voltage recovery rates and oscillography in connection with such tests, as well as the selection and operating performance of relay protective equipment for fault and out-of-step protection of lines, and surge current investigation in relation to the economics of lightning arrester installations.

Other papers for the program appear in this issue and still others will appear in succeeding issues up to the time of the convention so that ample opportunity will be afforded for advance study and the preparation of good discussion. Thus those in attendance will be assured of hearing excellent and pertinent discussions. They should also feel free to take part when the meeting is opened for general discussion.

In addition, and as a trial, plans also are being made to schedule a number of informal round table meetings for the benefit of specialists and the younger members. The success of several of these meetings at the winter conventions and the growing numbers of specialist groups which desire to meet periodically for discussion of their own problems have caused the technical program committee in coöperation with the summer convention committee to plan an enlarged program. The informal meetings will be sponsored by the technical committees through their subcommittee chairmen. Leaders in their respective fields will be invited to speak informally, and all of those interested will be invited to attend and participate in the discussion. No provision will be made for printing of papers, discussions, or conclusions reached at these informal round table meetings.

The purposes to be served by these round table meetings as planned are 4. First, it is hoped that various leaders in the art will be willing to speak informally at these meetings, pointing out the lines of future progress as they see them and commenting on recent developments. It is hoped that these talks will direct the work of the Institute committees into new and pertinent channels. Second, the programs will afford opportunities for meetings of groups of Institute members who are interested in specialized activities, but those subjects are of too little interest to the great majority of the membership to warrant publication in Electrical Engineering. Third, these round table discussions afford an opportunity for technical committees or their subcommittees to obtain assistance from individuals, not members of the committees, but interested in the particular subject under discussion. Fourth, if desirable, arrangements will be made for round table discussions confined specifically to those phases of the art which are of particular interest to students.

The chairmen of the technical committees are invited to sponsor round table meetings of their subcommittee groups. Suggestions from the members for subjects to be discussed should be sent to C. S. Rich, secretary, technical program committee, at Institute headquarters, and they will be forwarded to the technical committees for consideration and approval.

Membership—

Mr. Institute Member:

Our membership messages to you month by month are representative of the constancy with which the Section membership committees are continually carrying on their work.

You are doing your part of this work when you send in the names of persons who you feel should be invited to join the Institute.

Since May 1, 1934, the beginning of this Institute year, 685 applications for membership had been received as of February 1, 1935.

Chairman National Membership Committee

Reports on Committee Meetings Held During Winter Convention

DURING the recent winter convention of the A.I.E.E. held in New York, N. Y., Jan. 22–25, 1935, many of the general and technical committees of the Institute held meetings. A summary of each of these meetings is given in the following paragraphs, with the exception of the meetings of those few committees for which no adequate reports were available for publication. Activities of one of these, the standards committee, are reported month by month in the "standards" department of ELECTRICAL ENGINEERING.

Automatic Stations

At the meeting of the committee on automatic stations, a resolution was passed (unanimously) directing the chairman to appoint 5 members of this committee to membership in a telemetering subcommittee to be composed also of 5 members of the committee on instruments and measurements. Papers and activities pertaining to telemetering would be handled by the subcommittee. The portion pertaining to the general subject of power dispatching and supervisory control would be sent to the committee on automatic stations while the portion on design and applications other than power dispatching and load control would be given to the committee on instruments and measurements. The chairmanship of the subcommittee would be alternated each year between the 2 committees.

The revision of the subcommittee report on "Telemetering and Supervisory Control" is ready for publication. The policy on the method of publishing has not been settled and D. W. Taylor was appointed to settle the details with H. P. Charlesworth. It was recommended that the revised report be published in ELECTRICAL ENGINEERING.

Papers for a session at the next midwinter convention were discussed and it is believed that a sufficient number of good subjects will be available.

The subcommittee on the revision of standards number 26 will have their work completed on March 1, 1935. The old issue of May 1930 is badly in need of revision and it was recommended that this work be carried through promptly.

A partial summary is available on each of these subjects:

A. Storage battery charging in unattended station.
B. Effectiveness of protective devices.
C. The use of fuses in unattended stations.

Electrical Machinery

The committee on electrical machinery discussed the following subjects constituting the principal items that the committee is interested in at the present time.

Test Codes for Electrical Machinery. For the past 2 or 3 years the committee has been very active in preparing test codes for various types of electrical machinery. Preliminary reports on the test code for transformers, test code for polyphase induction machines, and test code for synchronous machinery, have been printed and can be obtained, free of charge, by applying to A.I.E.E. headquarters. The test code for d-c machinery is under preparation and it is expected that it will be completed during the coming year. These codes supplement the present A.I.E.E. Standards and are a valuable contribution to the Institute's publications, as they represent the most up-to-date methods in the testing of electrical apparatus, a phase of work which it is not possible to cover in the regular standards.

Round Table Discussions During National Conventions. The committee sponsored 2 round table discussions during the winter convention, one of these being on transformers and the other on the induction motor test code. These discussions were well attended and considerable interest was shown. At the induction motor test code discussion there were 7 prepared and written discussions and 4 oral discussions presented. The attendance at each discussion was around 25 or 30.

Insulation Resistance. No satisfactory rule has ever been worked out to determine the condition of electrical machinery by measurement of its insulation resistance. This question has become quite active and the committee has appointed a subcommittee with K. A. Reed, of the Hartford Steam Boiler Inspection and Insurance Company, as chairman to study the possibilities of formulating a rule that may be used by operators to determine, by means of its insulation resistance, when electrical machinery is not in a safe operating condition.

Electrochemistry and Electrometallurgy

The committee on electrochemistry and electrometallurgy continues to show the increased interest which is developing within the Institute membership in the importance of electrochemistry and electrometallurgy to manufacturers and users of equipment and to producers of power to serve such industries.

Considerable progress has already been made in the coördination of the committee's activities with those of other societies interested in similar work and further work will be done along this line. The committee has already established contact with representatives in England and Japan and will establish further contacts in foreign countries so that it will be kept informed as to activities throughout the world in the field of electrochemistry and electrometallurgy.

The plans for a session at the summer convention at Ithaca were presented and it can be said at this time that a most successful meeting is definitely assured.

The committee discussed the importance of directing its activities along the lines which are of most interest to the membership of the Institute and it is most encouraging to report a definite increase in the general interest displayed in the subjects which come under the scope of its activities and toward which its future programs are being directed.

A definite start has been made in formulating plans for next year's mid-winter convention.

Electrophysics

The committee on electrophysics at its meeting devoted much of the time to discussing plans for a series of round table discussions of subjects in the fields of physics, chemistry, and mathematics, which may be of interest and value to the electrical engineer. It is proposed to hold the first 2 of these at the time of the summer convention. One round table session will be devoted to a discussion of tensile analysis which is proving to be a very helpful tool in dealing with a number of complicated electrical circuit problems, such as the multicircuit transformer, rotating machinery, and vacuum tubes. Some interesting analogies have been developed between the phenomena in rotating electrical machinery and Einstein's space theories.

Another meeting will discuss X rays and their engineering application. It is planned to coördinate this meeting with some of the research in X rays being done at Cornell by Professor Richtmeyer and his associates.

Instruments and Measurements

At the meeting of the instruments and measurements committee the papers that had been submitted for possible presentation at the A.I.E.E. summer convention were discussed. It was decided to recommend that the paper "Definitions of Power, Power Factor and Related Quantities," by Doctors Curtis and Silsbee should be presented in its present form and be published in full. Among other papers discussed were "A Method of Precise Speed Control for Use in Measurement Work," by R. H. Frazier, J. Eisler, and W. P. Frantz; "The Design of Pivot Bearings for Indicating Instruments," by J. H. Goss; "Effect of Lubrication on the Life of Watthour Meter Bearings," by Abbott and Goss; and "The Surge Crest Ammeter—A New Instrument for Surge Current Measurements," by C. M. Foust.

Power Generation

At the meeting of the committee on power generation, there was formulated the tentative program for the session sponsored by this committee at the 1935 summer convention.

It is expected that there will be presented at this session a paper by H. M. Cushing, chief engineer of the Buffalo General Electric Company, covering some new features of the Huntley Station; a paper by R. E. Greene of the Detroit Edison Company, covering rehabilitation of generationg stations, and a paper by L. N. McClellan, chief electrical engineer of the United States Bureau of Reclamation, on the general subject of power production at Boulder Dam. It is planned also to include a third report of the subcommittee on hydroelectric survey.

There was considerable discussion of subjects which should be covered in the near future by papers sponsored by this committee and the committee members will endeavor to arrange that some of these subjects will be covered by papers to be presented at the next Mid-Winter Convention.

Power Transmission and Distribution

At the annual meeting of the power transmission and distribution committee the chairman outlined the committee's main activities in Institute work for the past year, namely, 2 sessions at 1934 mid-winter convention, 1 on transmission line problems and the other on distribution; 1 session at the annual convention at Hot Springs on insulators; 2 sessions at the Pacific Coast convention in Salt Lake City, 1 on lightning and 1 on transmission line subjects; and 2 sessions at the present mid-winter convention, 1 on transmission lines and the other on cable. Plans for the coming conventions were discussed.

Reports were then submitted by each subcommittee chairman on their activities, plans, what research they have sponsored, etc., during the past year and their plans for the future. These reports came from the following subcommittees: conductors, towers and poles; lightning and insulators; distribution; interconnection factors and stability; cable developments; and standards.

A report submitted by the subcommittee on conductors, towers, and poles on the prestretching of conductors was read and approved for publication.

Research

At the meeting of the committee on research it was reported that up to January 19th, 156 copies of the list of research suggestions prepared by the committee and announced in the November 1934 number of Electrical Engineering (also in a journal of the S.P.E.E.) had been issued to 100 individuals, 71 of whom applied to headquarters for copies of the list in response to the published announcements. Certain suggestions were made for giving the availability of this list further publicity. It was also agreed that a second list should be prepared for issuance in the fall. It is proposed to follow up each recipient of a copy of these lists with a view to determining how many of the suggestions have been actually taken up and what progress is being made.

An extended discussion was had of other means which are feasible at this time of calling attention to and encouraging research, particularly in educational institutions. A number of suggestions were made which will be acted upon.

The need for certain library researches in the electrical field was stressed in this discussion but it was agreed that such an effort to be worth while should be on an organized basis with some financial support rather than on a purely individual, voluntary basis.

Several fundamental experimental researches in various branches of the electrical engineering field were discussed—researches which ought to be under way on an organized and financed coöperative basis. One of these, dealing with liquid insulations, will, it is hoped, be initiated in the near future under the auspices of a group of utility companies. Two other researches involving pathological matters would be appropriate for support by one of the foundations operating in the medical field.

In lieu of a comprehensive annual review of published research work which the committee feels cannot be properly done through individual, voluntary effort, it was proposed that brief reviews of research accomplishments in each of those fields in which one of the committee members specializes be published "piecemeal" in Electrical Engineering during the year.

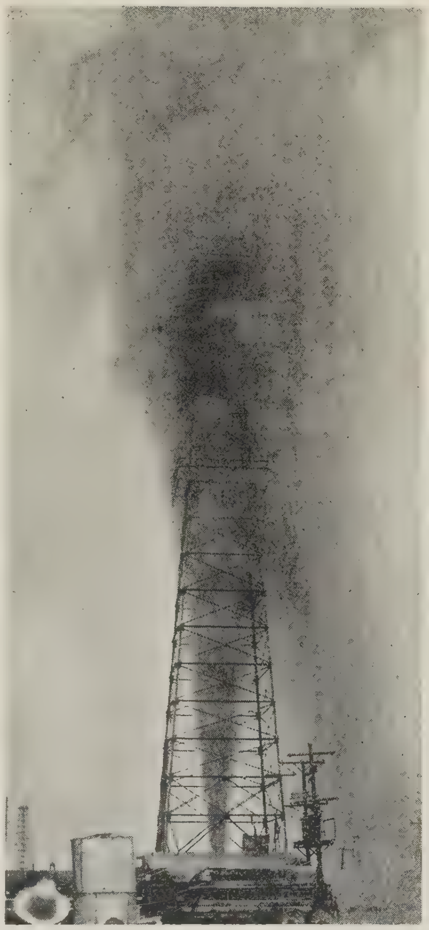
The arrangement of the details for carrying out some of the suggested plans was left to a small steering committee which can meet readily and as often as may be necessary.

Discussion on Noise

A discussion on noise was sponsored by the A.I.E.E. committee on sound, which is a subcommittee of the A.I.E.E. standards committee. At this afternoon discussion meeting, which in effect was an extension of the symposium on noise measurements held in the morning at which several Institute papers were presented, the discussion concerned principally with the papers which had been presented.

As a result of the interest shown at this meeting, it is tentatively planned to have an informal round table discussion on noise, without any printed papers, at the Institute's 1935 summer convention at Ithaca, N. Y. Emphasis at the proposed meeting would be placed upon the question of what are acceptable and generally existing noise levels under different living conditions.

An Oil Gusher in the Oklahoma City Oil Field



An oil gusher in the oil field adjacent to Oklahoma City, Okla., before it was placed under control. This oil field will be visited by most of those attending the South West District meeting of the A.I.E.E., to be held in Oklahoma City, April 24–26, 1935. This oil field, another view of which was shown in Electrical Engineering for February 1935, page 105, has 1,032 wells producing, with an average of one well for every 6 acres. The connected capacity for pumping and other purposes in this field is 25,000 horsepower; with the amount continually increasing. The Reda pump is used extensively in this field, the pump and motor being located in the bottom of a well, some installations being made as low as 6,000 feet below the surface. The motor varies in size from 75 to 110 horsepower and is placed inside the 6 inch casing.

Dates Selected for Pacific Coast Convention

The committee in charge of arrangements for the Institute's forthcoming Pacific Coast convention has definitely selected the dates of August 27–30, 1935, for the convention. It will be held at Seattle, Wash. Committees are being appointed and plans are being made for an interesting technical program and attractive entertainment features.

Translations Available From Engineering Library

Engineers and technical men in all parts of the country call on the service bureau of the Engineering Societies Library for exact, technically accurate translations because they know that they will find there a well equipped staff that can handle translations from any language and on any aspect of engineering.

The service bureau has translated more than 2,750,000 words from many languages in a 5 year period. Translations from German were required most frequently and made up about one-half of the total, but French, Italian, Spanish, Russian, and other languages are frequently called for. The service bureau keeps in its files a collection of more than 1,500 translations that may be obtained by paying a moderate revision and copying charge. Charges are moderate because they cover only the actual cost of doing the work.

For further information or rates write the Engineering Societies Library, 29 West 39th Street, New York, N. Y.

(Information on other services available from the Engineering Societies Library was given in Electrical Engineering for December 1934, pages 1668–9, and January 1935, pages 130–1.)

New Rules Governing Award of A.I.E.E. Prizes for Technical Papers

AUTHORS who plan to present papers before the Institute during the calendar year 1935, and others who may wish to submit papers for prizes, would do well to bear in mind that such papers are eligible for consideration for Institute prizes. These awards are made each spring for papers presented during the preceding calendar year and fall into 2 main classes, national and District prizes.

Important changes in the rules governing the award of A.I.E.E. prizes for technical papers have been made since the publication of the "Announcement of A.I.E.E. Prizes for Technical Papers" in ELECTRICAL ENGINEERING for December 1934, page 1665. The new rules, which entirely supersede the previous ones, and which are retroactive to include papers already presented during 1935, are as follows:

National Prizes

The following national prizes may be awarded each year at the discretion of the committee on award of Institute prizes:

1. Prize for best paper in: (1) engineering practice; (2) theory and research; and (3) public relations and education.
2. Prize for initial paper.
3. Prize for Branch paper.

The national prize for best paper in each of the 3 classes, namely, engineering practice, theory and research, and public relations and Education, may be awarded for the best original paper presented at any national, District, or Section meeting of the Institute, provided the author, or at least one of co-authors, is a member of the Institute.

The national prize for initial paper may be awarded for the most worthy paper presented at any national, District, Section, or Branch meeting of the Institute, provided the author or authors have never previously presented a paper which has been accepted by the technical program committee, and the author, or at least one of co-authors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

The national prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Enrolled Students of the Institute.

Only papers presented during the calendar year shall be considered for any of the prizes, except those for the best paper prize in the class of public relations and education. In this class, all papers presented subsequent to those considered at the time of the last previous award in this field will receive consideration. All papers approved by the technical program committee which were presented at the national conventions or District meetings will be considered for the best paper prizes and initial paper prize without being formally offered for competition. All other papers which were presented at Section, Branch, or Student meetings must be submitted in triplicate with written communications to the national secretary on or before February 15 of the following year, stating when and where the papers were presented. This may be done by authors, by officers of the Institute, or by the executive committees of Sections or geographical Districts.

Each national prize shall consist of a certificate of award issued by the Institute and \$100 in cash. When papers are written jointly, the cash awards shall be divided and a certificate shall be issued to each author. The board of directors may, at its discretion, omit the cash awards for any of the prizes.

Committee on Award of Institute Prizes. This committee shall consist of the chairman of the technical program committee, acting as chairman; the chairmen of the publication committee, the committee on research, the technical program committee of the previous year, and the chairmen of such other committees as the board of directors may designate. This committee shall award at its discretion all the national prizes. It may award a single paper more than one of the prizes available and it may make honorable mention of papers which do not receive prize awards. All the national prizes for a given calendar year shall be awarded prior to May 1 of the succeeding year. They shall be presented at the next summer convention of the Institute.

For the national best paper prizes the technical program committee shall indicate to the committee on award of Institute prizes the class under which each paper is to be considered for first prize.

Basis of Grading Papers. The technical committees shall assist the committee on award of Institute prizes by grading papers at the time they are initially reviewed for acceptance. The valuations which shall govern the grading of papers for purposes of making awards shall be as follows:

Analysis of Subject..................10 per cent

The paper shall present a clear outline of the situation out of which arises the need for the preparation of a paper on the particular subject, explaining the point of view assumed in the presentation.

Logical Presentation.................10 per cent

The presentation should include an analysis of the difficulties encountered, the methods of attack and the solution of the problem.

Originality...............................10 per cent

Credit should be given to the paper which brings to its subject matter a fresh point of view, a healthy open-mindedness or a discarding of some outworn traditions.

Unity.....................................10 per cent

While brevity and conciseness are important they should not be attained at the sacrifice of unity and completeness of presentation.

Value in Its Field....................30 per cent

The value of the paper as a contribution to the literature in its own field should receive particular consideration.

Value to Electrical Engineering........30 per cent

The paper should be considered from the standpoint of the quality of its contribution to the advancement of electrical engineering and its value to civilization.

Publication. Papers awarded prizes shall be published in full or in abstract, in ELECTRICAL ENGINEERING, in the TRANSACTIONS, or in pamphlet form:

District Prizes

The following District prizes may be awarded each year in each geographical District of the Institute:

1. Prize for best paper.
2. Prize for initial paper.
3. Prize for Branch paper.

The District prize for best paper may be awarded for the best paper presented at a national, District, or Section meeting, provided the author, or at least one of co-authors, is a member of the Institute.

The District prize for initial paper may be awarded for the most worthy paper presented at a national, District, Section, or Branch meeting, provided the author or authors have never previously presented a paper before a national, District, Section, or Branch meeting of the Institute, and the author, or at least one of co-authors, is a member of the Institute or is a graduate student enrolled as a Student of the Institute.

The District prize for Branch paper may be awarded for the best paper based upon undergraduate work presented at a Branch or other Student meeting of the Institute, provided the author or authors are Enrolled Students of the Institute.

Each District prize may be awarded only to an author who, or to co-authors of whom at least one, is located within the District, and for a paper presented at a meeting held within, or under the auspices of the District.

Only papers presented during the calendar year shall be considered. They must be submitted in duplicate by the authors or by the officers of the Branch, Section, or District concerned to the District secretary, on or before February 15 of the following year.

Each District prize shall consist of a certificate of award issued by the officers of the geographical District and \$25 in cash. When papers are written jointly, the cash awards shall be divided and a certificate shall be issued to each author. The board of directors may, at its discretion, omit the cash awards for any of the prizes.

Committees on Awards. All the District prizes for a given calendar year shall be awarded prior to May 1 of the succeeding year by the District executive committee or by a committee appointed by the District executive committee and authorized to make such awards.

Basis of Grading Papers. The valuations which shall govern the grading of papers for purposes of making awards shall be the same as those for the national prizes but the papers will not be graded by the technical committees.

Copies of a pamphlet entitled "National and District Prizes" may be secured, without charge, upon application to Institute headquarters. The information given in this pamphlet is identical with that presented above. These rules were originally adopted by the Institute's board of directors June 23, 1927; they were revised December 7, 1928, January 27, 1932, and January 21, 1935. The rules given above include the latest revisions.

E.C.P.D. Plan for Accrediting Engineering Colleges

THE work in which the Engineers' Council for Professional Development is now actively engaged is being carried on by its 4 working committees, namely, the committee on student selection and guidance, committee on professional training, committee on engineering schools, and committee on professional recognition. In an article "E.C.P.D. Reports Substantial Progress During 1934" which appeared in ELECTRICAL ENGINEERING for February 1935, pages 249–50, a brief résumé of the work accomplished by these 4 committees was given. Further details of the work of the committee on engineering schools is given in the present article.

The board of directors of the A.I.E.E. on May 25, 1934, approved the E.C.P.D. as an agency for the accrediting of engineering schools, but at that time reserved the right to approve the actual working plan for such accrediting. This working plan as developed by E.C.P.D. was transmitted to the A.I.E.E. November 19, 1934, and was considered at the meeting of the Institute's executive committee on December 7, but that committee felt that action should be deferred until the plan could be considered by the full board of directors. As announced in the above-mentioned article in the February issue of ELECTRICAL ENGINEERING, the Institute's board of directors on January 21, 1935, decided to sanction the plan as submitted. As also announced in that article, all societies concerned have now given the authorization needed to inaugurate the accrediting procedure; in addition to the A.I.E.E., the other participating bodies are The American Society of Mechanical Engineers, American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, Society for the Promotion of Engineering Education, the National Council of State Boards of Engineering Examiners, and the American Institute of Chemical Engineers.

E.C.P.D. through its committee on engineering schools announces the following principles and procedures in accordance with which accrediting will be conducted:

Basis for Accrediting

I. Purpose of accrediting shall be to identify those institutions which offer professional curriculums in engineering worthy of recognition as such.

II. Accrediting shall apply only to those curriculums which lead to degrees.

III. Both undergraduate and graduate curriculums shall be accredited.

IV. Curriculums in each institution shall be accredited individually. For this purpose, the E.C.P.D. will recognize the 6 major curriculums: chemical, civil, electrical, mechanical, metallurgical, and mining engineering—represented in its own organization, and such other curriculums as are warranted by the educational and industrial conditions pertaining to them.

V. Curriculums shall be accredited on the basis of both qualitative and quantitative criteria.

VI. Qualitative criteria shall be evaluated through visits of inspection by a committee or committees of qualified individuals representing the E.C.P.D. The visits of inspection either as to entire institutions or as to specific curriculums may be waived at the discretion of E.C.P.D.

VII. Quantitative criteria shall be evaluated through data secured from catalogs and other publications, and from questionnaires.

VIII. Qualitative criteria shall include:

1. Qualifications, experience, intellectual interests, attainments, and professional productivity of members of the faculty.
2. Standards and quality of instructions: (*a*) in the engineering departments; and (*b*) in the scientific and other coöperating departments in which engineering students receive instructions.
3. Scholastic work of students.
4. Records of graduates both in graduate study and in practice.
5. Attitude and policy of administration toward its engineering division and toward teaching, research, and scholarly production.

IX. Quantitative criteria shall include:

1. Auspices, control, and organization of the institution and of the engineering division.
2. Curriculums offered and degrees conferred.
3. Age of the institution and of the individual curriculums.
4. Basis of and requirements for admission of students.
5. Number enrolled: (*a*) in the engineering college of division as a whole; and (*b*) in the individual curriculums.
6. Graduation requirements.
7. Teaching staff and teaching loads.
8. Physical facilities. The educational plant devoted to engineering education.
9. Finances; investments, expenditures, sources of income.

The purpose of E.C.P.D. is to substitute a single accrediting for the uncoördinated methods that have been used in the past; E.C.P.D., representing the national engineering societies, the state licensing boards, and the colleges of engineering, is the only agency that can accredit colleges under properly inclusive auspices. As a not unimportant incidental advantage, accrediting by this one agency will avoid the needless duplications of present procedures.

E.C.P.D. is merely authorized by its constituent organizations to publish a list of accredited colleges for use by those agencies which require such a list. It has no authority to impose any restrictions or standardizations upon engineering colleges, nor does it desire to do so. On the contrary, it aims to preserve the independence of action of individual institutions and to promote the general advancement of engineering education thereby.

As stated in the foregoing paragraphs headed "Basis for Accrediting" appraisal of institutions will be based upon statistical information as obtained from catalogs and questionnaires, and upon evidence of quality of instruction, adequacy of equipment, and of teaching staff, and other factors not susceptible of statistical analysis, as determined by visits of inspection by committees of qualified representatives of the committee on engineering schools. Emphasis will be given to quality of work rather than to statistical information to a greater degree than in former accrediting procedures. No hard-and-fast prescriptions are laid down for the curriculum, the physical facilities, the investment or expenditures, or other specific points relating to a given institution, though all of these, and others will be taken into account in appraising the institution as a whole.

Final decision as to accrediting of each institution rests with the E.C.P.D. which will pass upon the recommendations made to it by the committee on engineering schools.

The general expenses of developing the accrediting program will be borne in part by a grant of funds from Engineering Foundation. Expenses of the visiting committees representing the Council will be met by a charge made to the individual institutions sufficient to cover cost of travel and subsistence during the inspection. This is in accord with the practice of certain other accrediting agencies.

Committees of inspection will comprise both teachers and practicing engineers, the criteria for selection being competency to judge educational institutions, good judgment, and availability. For the purposes of organization and administration of the accrediting program the country has been divided into 7 geographical regions which include within their boundaries approximately equal numbers of engineering colleges; New England, the Middle Atlantic States and Maryland, the Southeastern States, the Upper Mississippi Valley, the Lower Mississippi Valley, the Southwest, and the Northwest. Committees in the 7 geographic areas will include representatives of each of the organizations consituting the E.C.P.D. Alternates will be provided who will serve instead of the regular members when the latter would be called upon to judge a neighboring or rival institution, or the one with which the individual himself is connected. A member of the E.C.P.D. committee on engineering schools will serve as chairman of each regional committee.

Accrediting of individual institutions and of curriculums offered by them will be, of course, upon invitation of the institutions. Formal notification of the launching of the accrediting program will be sent by the committee to officials of the institutions in the near future.

The membership of the E.C.P.D. committee on engineering schools was given in the previously mentioned article in ELECTRICAL ENGINEERING for February 1935, page 249–50, along with the membership of the other E.C.P.D. committees. Inquiries as to any phase of accrediting should be addressed to the committee on engineering schools, Engineers' Council for Professional Development, George T. Seabury, secretary, 29 West 39th Street, New York, N. Y.

Information Committee Appointed

Supplementing the list of the members of the various E.C.P.D. committees given in the article in the February issue, the following committee, not included therein, is in charge of publicity and information released by the E.C.P.D.:

Information Committee

DR. H. C. PARMELEE, *chairman*, vice president, McGraw-Hill Publishing Company, Inc., New York, N. Y.

GEORGE A. STETSON, editor, The American Society of Mechanical Engineers, New York, N. Y.

SIDNEY WILMOT, manager of publications, American Society of Civil Engineers, New York, N. Y.

E. H. ROBIE, assistant secretary and editor, American Institute of Mining and Metallurgical Engineers, New York, N. Y.

G. ROSS HENNINGER (A'22, M'27) editor, American Institute of Electrical Engineers, New York, N. Y.

Another High Speed Diesel-Electric Train

External streamlining and internal comfort feature the railroads' constructive bid for increased passenger travel

THE new "Flying Yankee," diesel-electric 3-unit train delivered by the Edward G. Budd Manufacturing Company (Philadelphia, Pa.) to the Maine Central-Boston and Maine Railroad, is the first such unit to be placed in regular operation on an eastern railroad. On a trial run February 5, 1935, on a short stretch of track out of Philadelphia, this train attained a speed of 100 miles per hour with a substantial passenger load. From a practical operating standpoint, the rapid and smooth acceleration and retardation were particularly noteworthy, comparative data showing that by the time this train and a comparable steam train could reach a 90 mile an hour cruising speed, the "Flying Yankee" would be some 6 miles ahead of the steam train. This is a particularly important matter in connection with local service.

Reflecting the successful pioneering operation of the now famous "Zephyr" placed in service last year between Lincoln, Neb., and Kansas City, Mo., by the Burlington Railroad, the "Flying Yankee" is a 3-section 4-truck articulated unit of light weight stainless steel construction, completely self-contained and air conditioned. Providing seats for 144 passengers in addition to an engine room, a baggage department, and an electrically equipped buffet, the over-all length of the unit is 199 feet $2^3/_4$ inches; its weight about 106 tons complete. The weight of a complete steam train replaced by a lightweight unit of this kind is in the neighborhood of 400 tons. An ordinary pullman car weighs nearly as much as the lightweight train. Another important feature of the lightweight train is its economy of operation; ordinary furnace oil is used as fuel.

In the "Flying Yankee" a 600 horsepower 2 cycle 8 cylinder Winton diesel engine supplies power to the forward trucks of the train through the medium of a direct connected differentially wound d-c generator which feeds the 2 traction motors mounted on the driving axles. Principal mechanical equipment including engine and air conditioning apparatus was supplied by the General Motors Corporation; electrical equipment including generators, traction motors, and control system by the General Electric Company.

In connection with the actual construction of the "Flying Yankee" and other similar units now in the Budd shops, is the fact that the entire train with the exception of truck mountings was fabricated from thin sheets of special high strength steel literally built up piece by piece by a special electric spot welding process. This process has been termed the "shotweld" process by the Budd company because both the amount and duration of current flow to each spot weld is subject to automatic control by means of an electronic device after having been predetermined according to the weight of the particular sheets to be welded. Thus the welding operator merely clamps the 2 sheets between the electrodes of his hand tool and pulls the trigger, welding up to 20 or more spots per minute.

The "Flying Yankee" is scheduled to be placed in regular service making a daily run from Portland, Me., to Boston, Mass., a round trip from Boston to Bangor, Me., and an evening run from Boston back to Portland, a daily schedule of nearly 700 miles.

Safety Engineers' Society Suggests Coöperation

The American Society of Safety Engineers, engineering section, of National Safety Council through its committee on coöperation with other engineering societies, has taken steps to bring about the coördination of the technical aspects of safety work now being carried on by different organizations. It is the hope of this committee that the work of all engineering societies and interested technical and industrial agencies in handling the technical aspects of accident prevention may be properly correlated.

The plan of procedure proposed by the committee consists of the appointment of a member of the A.S.S.E. executive committee to be the contact man with each of the engineering societies and other organizations concerned; the appointment by these other organizations of their contact man to work with the A.S.S.E.; the establishment of relations with the various industrial sections of National Safety Council; the interchange of information between all interested agencies; and the rendering of assistance to the committee for development of interest in safety education in technical colleges.

Inasmuch as the A.I.E.E. is cognizant of the importance of the technical aspects of accident prevention and desires to coöperate in the exchange of information, it has taken steps to supplement the individual contacts of the Institute's membership already existing with other engineering societies and industrial organizations. Therefore, the appointment has been announced of F. D. Knight, chairman of the Institute's committee on safety codes, as the A.I.E.E. contact man with the A.S.S.E. He will consult the membership of the committee on safety codes and secure the benefit of their judgment in all matters referred to him.

Montefiore Prize Award Still Open. Announcement that the Montefiore prize award constituting the interest on 150,000 Belgium francs, distributed triennially in international competition for the best original work presented on scientific advancement and progress in technical application of electricity, is open to candidates, was given in ELECTRICAL ENGINEERING for June 1934, page 1026. Conditions governing the award were given therein. The final date for the reception of manuscripts by the jury has been fixed as April 30, 1935. Communications should be addressed to Omer De Bast, president of the Montefiore Foundation, Rue Saint Gilles, 31, Liege, Belgium.

Engineering Index Plans Expansion

Engineering Index, Inc., will appeal to the nation's industry operating in technical fields for a working capital fund of approximately $160,000 with which to continue the service and spread its use throughout the engineering offices, libraries, and colleges of the country, over a 5 year period after which it is estimated it will be self-sustaining. This project has just been announced by Collins P. Bliss, dean of the school of engineering at New York University and president of the board of directors of the Index.

Thus will this 50-year-old engineering institution enter a new and wider field, according to Dean Bliss. At the annual meeting of The American Society of Mechanical Engineers in 1933 it was voted to discontinue the society's responsibility for, and financial losses accruing from, the operation of the Index. This decision became effective the beginning of 1934. In June of 1934 the Index was formally incorporated as a nonprofit organization in its own right. This followed an extensive study by an outside organization which developed the conclusions that if it were not for the Index, the engineering field would be without a complete and effective organization of its current literature. To those not already familiar with the Index, it may be described as a virtually complete catalogue, with annotations, of technical literature in all branches of engineering. The merits claimed for the service include completeness, descriptiveness, promptness, and accuracy.

The Index is published in 2 separate forms. The annual volume is roughly similar to complete indexes in other scientific fields. More unique is the card service which is a cumulative card index of technical literature sub-divided into approximately 280 divisions which may be had in any desired combination. About 2,000 publications are reviewed by Index editors. These periodicals come from 40 different countries and are in 20 languages.

The present board of directors includes, besides Dean Bliss, H. V. Coes, manager of the industrial department of Ford, Bacon, and Davis; R. E. Flanders, president of Jones and Lamson Machine Company; R. M. Gates, vice president of Combustion Engineering Company, Inc.; and C. F. Hirshfeld (A'05), chief of the research department of Detroit Edison Company. The charter of the Index, which describes the typical membership nonprofit corporation under the New York State law, provides for 50 trustee members who Dean

A Reading List for Junior Engineers

A LIST of books recommended for reading by junior engineers has been prepared by a number of eminent men, many of them distinguished in the engineering profession. Sections of this list have been published in ELECTRICAL ENGINEERING for December 1934, page 1667, and January 1935, page 133. Another section is published herewith, and others are scheduled to follow in subsequent issues. The complete list includes more than 100 titles.

Systematic reading of worth while books adds breadth and vision to the background of an engineer and should be considered a part of the intellectual development designed to fit the young engineer for full professional recognition. It is suggested that over a period of about 4 years a minimum of about 25 of these books might be selected and read, with the limiting recommendation that the selection made will include at least one book in each classification, preferably in accord with the individual engineer's most vital interests.

Economics and Sociology

Mexico: A Study of the Two Americas, Stuart Chase. Macmillan, 1931. A thought-provoking contrast between 2 civilizations—the one based on handcraft and the other on machines.

Guide Through World Chaos, G. D. H. Cole. Knopf, 1932. Survey of world crisis and its background of war conditions and in the light of capitalism of past 2 centuries. Valuable material for discussion of communism and capitalism.

Introduction to Sociology, Carl Dawson and Warner Gettys. Ronald Press, 1929. Statement of fundamental sociological principles. Many concretely described social situations relating to urban life and economic activities.

Causes of Industrial Unrest, J. A. Fitch. Harper, 1924. Judicial consideration of prevailing conditions and phenomena which cause and contribute to industrial unrest, but makes no attempt at a solution.

Taming Our Machines, R. E. Flanders. R. R. Smith, 1931. Attainment of human values in a mechanized society. Written in popular manner—clear and simple. A fresh view of the world's present troubles.

Economic Stabilization in an Unbalanced World, A. H. Hansen. Harcourt, Brace, 1931. Treats: 1, international causes of instability; 2, causes of world-wide unemployment; 3, population stabilization; 4, discussion of value of possible or desirable stabilized capitalism.

Economic History of the United States, E. F. Humphrey. Century, 1931. Narrative of economic development of United States, for purpose of discovering conditions of today from a record of country's growth.

Constructive Citizenship, L. P. Jacks. Doubleday, Doran, 1928. He has "brought into captivity many ideas which have waged a solitary fight in isolated places, and has regimented them into such shape that they deal a smashing blow against mechanical schemes of social deliverance."

Man's Rough Road, A. G. Keller. Yale University Press, 1932. A study of age-old institutions—property, religion, and marriage, especially in primitive manifestation. Condensation of a 4-volume work.

Industrial Economics, Dexter S. Kimball. McGraw-Hill, 1929. Discussion of industrial history, the high lights of which are handcraft production, the industrial revolution, and the effect of mechanical inventions. This is followed by a discussion of major topics, such as, division of labor, production economics, management principles, etc.

Middletown: A Study in Contemporary American Culture, R. S. and H. M. Lynd. Harcourt, Brace, 1929. A painstakingly statistical, yet sympathetic appraisal of a typical small city.

The Meaning of a Liberal Education, Everett Dean Martin. Norton, 1926. Discusses what education is, and is not; condemns utilitarian aim so prevalent today, and pleads for education which will reveal spiritual values of life.

Capital, Karl Marx. Kerr, 1919. A critique of political economy. Written originally to make plain the fallacy of capitalistic economy, and is still held to be the source from which anti-capitalistic movements draw their constructive power.

Principles of Political Economy, With Some of Their Applications to Social Philosophy, J. S. Mill. Appleton, 1898. Abridged edition, with critical, bibliographical and explanatory notes and a sketch of the history of political economy, by J. L. Laughlin.

Economic Tendencies in the United States, F. C. Mills. Little, Ives, 1932. Statistical study from 1900 to 1929 of economic conditions.

Readings in the History of Economic Thought, S. H. Patterson. McGraw-Hill, 1932. Selected readings omitting recent ideas. Arranged by schools of thought from times of earliest expositions of economics down to neo-classicism. Stresses minor rather than major orthodoxies.

Recovery: The Second Effort, Sir Arthur Salter. Century, 1932. Analyzes the broad causes which have brought the world into the present state of distress and indicates new requirements, economic, financial, commercial, and political, upon which to base a new world order.

America Comes of Age; a French Analysis, Andre Siegfried. Harcourt, Brace, 1927. Analysis, by a keen observer, of our ethnic, economic, and political situation. Displays extraordinary insight into the characteristics of American civilization.

Wealth of Nations, Adam Smith. Putnam, 1904. Inquiries into the nature and cause of wealth of nations. A landmark in history of thought, but parts are now out of date.

A Planned Society, George Soule. Macmillan, 1932. Critical analyses of our present unmanaged civilization, followed by an attempt to build up case for economic planning. Informed and well-balanced discussion of need for social plan.

Industrial Discipline and the Governmental Arts, R. G. Tugwell. Columbia University Press, 1933. An economist's picture of the social machine guided by government to achieve more perfect adaptation to machine society.

Bliss says, are to represent all the important engineering bodies in the country.

The plans for the campaign call for a national campaign committee, and local committees for each of 12 industrial centers. National committee headquarters have been established in the Engineering Societies' Building at 29 West 39th Street, New York, N. Y.

Japanese Government Bestows Honors. Clark H. Minor, president of the International General Electric Company, and Dr. Irving Langmuir, associate director of the research laboratory of the General Electric Company at Schenectady, N. Y., have recently been awarded the Fourth Order of the Rising Sun by the Japanese government. Doctor Langmuir has also been elected an honorary member of the Institute of Electrical Engineers of Japan, as reported in ELECTRICAL ENGINEERING for January 1934, pages 129–30.

A.I.M.E. Elects Officers. Election of officers for the American Institute of Mining and Metallurgical Engineers for the coming year was made during the recent A.I.M.E. convention held in New York, N. Y., Feb. 18–21, 1935. The individuals elected took office on February 19. H. A. Buehler, a geologist, was elected for the office of president. John M. Lovejoy, president of the Seaboard Oil Company, and Paul D. Merica, of the International Nickel Company were elected as vice presidents. As directors of the A.I.M.E., the following were elected: C. K. Leith, chairman of the department of geology at the University of Wisconsin, Madison; Edwin E. Ellis, vice president of the U.S. Steel Corporation in charge of mining, raw materials, and lake shipping; Wilber Judson, vice president of the Texas Gulf Sulphur Company; Ralph M. Roosevelt, vice president of the Eagle Picher Lead Company; and Wilfred Sykes (A'09, F'14) assistant to the president in charge of operation for the Inland Steel Company.

Electrochemical Society to Meet. The spring meeting of the Electrochemical Society will be held March 21–23, 1935, at New Orleans, La. Requests for information regarding this meeting should be addressed to Mr. Colin G. Fink, secretary of the society, in care of Columbia University, New York, N. Y.

Bulletin on Unbalance in A-C Machines. A study of the operating conditions of a-c machinery when operating under a partial or full load, entitled, "Unbalance in Alternating Current Machines," by DR. E. M. SABBAGH (A'28), of the Purdue University school of electrical engineering, has been published in bulletin form recently by the Purdue Engineering Experiment Station. The study is the result of a long and theoretical investigation confirmed by experimental test results of practical conditions of operation. The comparatively recently developed method known as symmetrical components has been applied by Doctor Sabbagh to the analysis of a-c machinery when operating under normal loads. This analysis points out the conditions of limiting loads and voltage regulation under operating conditions which, although abnormal, are often met in practice. Copies of the bulletin may be obtained by writing to the Purdue University Engineering Experiment Station, Lafayette, Ind.

Consulting Engineer and Former Professor Dies. Harry de Berkeley Parsons, consulting engineer of New York, N. Y., died January 26, 1935. He had been professor of steam engineering at Rensselaer Polytechnic Institute from 1891 to 1907. Mr. Parsons was born at New York, and received the degrees of bachelor of science from Columbia University in 1882 and mechanical engineer from Stevens Institute of Technology in 1884. After several years of railroad engineering in Texas he entered the field of mechanical engineering and for 16 years was at Rensselaer Institute, leaving with the title of professor emeritus of practical engineering. As a private consultant he served New York City on street cleaning and waste disposal problems, and was chairman of the commission on street cleaning and waste disposal and a member of the metropolitan sewerage commission 1908–1914. Mr Parsons was president of the Institute of Consulting Engineers in 1926, and a member of the American Society of Civil Engineers. In 1925 he was awarded the Rowland prize, and in 1930 the Croes medal.

Dean Ketchum Dies. Milo S. Ketchum, former director and vice president of the American Society of Civil Engineers, past president of the Society for the Promotion of Engineering Education, and dean of engineering at the college of engineering, University of Illinois since 1922 (emeritus since 1933) died in Urbana, Ill., December 19, 1934, at the age of 63. A native of Illinois, he graduated from the University of Illinois in 1895, took his civil engineering degree in 1896. His career as an engineering teacher began at the University of Illinois immediately after his graduation where he served as a faculty member from 1895 to 1897, again from 1899 to 1903, and finally from 1922 to the time of his death. With the intervening years spent in field service as a bridge and structural engineer, Dean Ketchum was professor of civil engineering at the University of Colorado from 1904 to 1905, dean of his department from 1905 to 1919; he was professor of civil engineering at the University of Pennsylvania from 1919 to 1922. Dean Ketchum was a prolific technical writer on civil engineering subjects.

Construction Camps for the Grand Coulee Project

GENERAL view of Coulee City, the government camp site which will house the men and their families who will construct the PWA irrigation dam and power plant of the Grand Coulee project in the Columbia River basin, Wash. Across the river can be seen Mason City, the contractor's town site. The construction railroad connecting the Northern Pacific Railroad with the dam site has been completed, and work on the dam and power plant is being carried forward under the contract awarded last fall. It is reported that this project will cost $63,000,000, the Public Works Administration having made an initial allotment of $15,000,000 to carry on the work.

Municipal Engineers and Public Works Officials Establish Joint Organizations. A policy of expanded service to members of the engineering and public works professions was recently announced by the American Society of Municipal Engineers and the International Association of Public Works Officials, upon the establishment in Chicago, Ill., of a joint secretariat for the 2 organizations. The secretariat will be administered by a joint board of 4 members from each association, with Donald C. Stone as executive director. It is planned to make available to member municipal engineers and public works officials a clearing house of information on their current problems and to perform various other services to aid them in their profession of municipal service. Local, state, and regional chapters to encourage coöperation of public works officials within an area will be fostered by the association. The first joint annual conference of members of the 2 societies, which have a total membership of 1,000 is scheduled for Cincinnati, Ohio, during October 1935.

as the graphical mapping but did want to call attention to the originators of this method since the textbook by S. S. Atwood on "Electric and Magnetic Fields" gives a rather extensive modern presentation of the principles. Unfortunately, this book, as so many "textbooks," does not give any references.

Very truly yours,

ERNST WEBER (A'31)
(Research Prof. of Elec. Engg., Brooklyn (N. Y.) Polytechnic Institute)

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or to reject them entirely.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

CORRECTION—Figure 1 of the "Letters to the Editor" by David J. Ball entitled "Graphical Solution of Star-Delta Transformations" in the December 1934 issue of ELECTRICAL ENGINEERING, page 1680, is in error in that y_C should have been extended to the next lower dashed line; the distance which y_C should extend is indicated correctly in figure 2 on the same page. Regarding the practical use of this graphical solution, the author states that the greatest advantage over a purely mathematical solution results when the diagram is constructed on "polar coördinate graph paper with a triangle as the only instrument, reading the required values directly from the paper without the use of a scale. If necessary, a special graph paper can be constructed consisting of concentric circles and vertical lines with a rigid arm rotating about the center to indicate various radii as they are required in reading the graph. With a device of this sort a solution may be obtained from the graph with no actual construction work and with approximately the same ease as is obtained in reading a curve.

Mapping of Fields

To the Editor:

The following refers to the "Letters to the Editor" by J. F. Calvert and L. A. Kilgore (see ELECTRICAL ENGINEERING, February 1935, pages 253–4) discussing the paper "Mapping of Fields" by Ernst Weber, which appeared in ELECTRICAL ENGINEERING for December 1934, pages 1563–70.

Mr. Calvert has worked extensively in the development and application of the semigraphical methods of field mapping and any contribution on his part is, therefore, to be highly appreciated. As I stated in the last paragraph of the section on "Graphical and Semigraphical Mapping" (page 1565 of the December 1934 issue), these "methods are of utmost value in all design problems. . . . ." but they have their limitations. As I had worked rather extensively at the Siemens-Schuckert Company in this particular field I had more than one opportunity to long for a general mathematical solution from which general conclusions might be drawn, especially in the case of commutation of large d-c machines, a-c machines, and the pole form and leakage flux evaluations of large a-c generators. I may recall at this point the simple formulas, used in transformer leakage, slot, tooth, and end leakage of machines, which had been derived once with high rigor and simplified by practical experience until now there is hardly need for graphical detail work. The other more complex problems are as yet in the preliminary stage of graphics. If more use were made of mathematical mapping, probably some ambitious younger engineer would sit down and develop a few fundamental formulas which, with at least the same degree of approximation, could replace months of graphical work. With this I do not want to discredit graphical mapping at all—only to indicate future developments and to justify the stress laid in my paper upon the less known methods and their possibilities. As Mr. Calvert indicated in his last paragraph, only when mathematical detail work can be omitted is there assured wide application of a method. So also for mathematical mapping of fields. Once the formulas have been developed there should be no need for mathematical or graphical detail work and consequently more economy in design would take place, which is rather important because relatively few designs are ever actually carried out in practice.

The additions to the bibliography by Mr. Kilgore are extremely helpful to the student of graphical methods. There are, in fact, numerous papers and discussions in all periodicals of the civilized countries dealing with graphical mapping in all fields of engineering. I did not feel justified to take up much space with a method as well developed

Overcompounded D-C Generators in Parallel Without an Equalizer

To the Editor:

The renewed interest in the problem of the operation of 2 overcompounded d-c generators in parallel without an equalizer, promps us to submit a résumé of our paper which was presented at the A.I.E.E. student convention, New York Section, on April 26, 1934. (Previous "Letters to the Editor" on this subject have appeared in ELECTRICAL ENGINEERING as follows: by J. G. Brainerd, volume 51, October 1932, page 745; by O. W. Walter, volume 53, November 1934, pages 1553–4; by J. G. Brainerd, volume 54, January 1935, page 135; and by J. O. Reid, this issue, pages 348–9.

Doctor Pender, in his text "Direct Current Machinery," states that if the speed of one of the generators should increase slightly, due to any cause, thereby giving that generator a higher regulation curve,

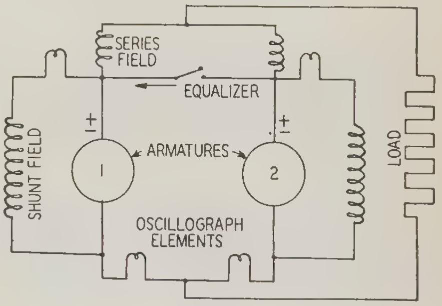


Fig. 1

the current output of that machine would decrease. Evidently those who oppose this statement have not offered sufficient evidence to either prove or disprove the argument of Doctor Pender and his associate, Professor Brainerd.

Keeping in mind the fact that Doctor Pender specifies variable speed as one of the requirements of the test, we first determined the other variables influencing the instability by coupling both generators to the shaft of a synchronous motor.

Connecting the 2 generators with their series fields to the positive side of their respective armatures (figure 1), the field currents of each machine were so adjusted that the equalizer current flowed from machine 2 to machine 1. Upon opening the equalizer bus, the equalizer component of the armature current of machine 2 is made to flow through its series field in the same

direction as the line current flows in the steady state. Thus, this increased current must strengthen the series field, resulting in an increased induced electromotive force. On the other hand, the current through the series field of machine 1 is decreased, causing a proportionate decrease in its electromotive force. The difference between the electromotive forces of the machines causes a current to circulate in a counterclockwise direction, further increasing the induced electromotive force of machine 2, and decreasing the electromotive force of machine 1. This obviously results in a larger circulating current. The action is thus cumulative, causing machine 2, the machine with the greater electromotive force, to take all of the load and perhaps drive machine 1 as a motor. The oscillogram (figure 2), clearly shows the transient condition which exists. Upon opening the equalizer, the current I_2 increases and the current I_1 decreases. The equalizer bus was closed before the line circuit breakers opened and all steady state values were resumed. When the equalizer current was made to flow in the opposite direction, from machine 1 to machine 2, the generator which formerly took the greater load now lost it; the machine which previously surrendered now assumed the load (figure 3). Therefore the results show that if the series fields are connected to the positive side of their respective armatures, the current in the equalizer will flow away from the machine which would take the load if the equalizer were opened. By similar reasoning it can be readily seen that if the series fields are connected to the negative armature terminals, the equalizer current will flow toward the machine which would take the load. The explanation of an increasing electromotive force with increasing

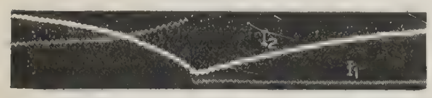


Fig. 2

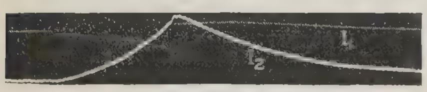


Fig. 3

load is the analysis to which Professor Walter referred, November 1934 issue of Electrical Engineering, page 1553, when he stated that our views were contrary to those of Doctor Pender.

Another important observation that was made with the generators still connected to the synchronous motor was the relationship between the line and field currents of both machines. Reconsider the case where generator 2 takes the load. With the equalizer closed, the direction of the currents in the shunt and series fields and the resultant flux ϕ_f, are as indicated in figure 4. When the equalizer bus is opened, the current through the series field rises at an increasing rate, because of the cumulative action of the system. The resulting flux in the field poles increases, inducing an electromotive force in the series and shunt field windings. This induced electromotive force in the shunt field winding opposes the normal flow of shunt field current. Since the electromotive force varies at an increasing rate, the resultant shunt field current must decrease proportionately, even though the load taken by this machine increases (figure 5). Similarly, it was found that the shunt field current of the machine which loses the load increases cumulatively.

In order to determine the effect of variable speed, as required by Doctor Pender, the generators were removed from the shaft of the synchronous motor and were driven by independent prime movers. Under these conditions, oscillograms of speed and line current of each of the machines were taken. From the oscillograms it was observed that the variations of the speed and

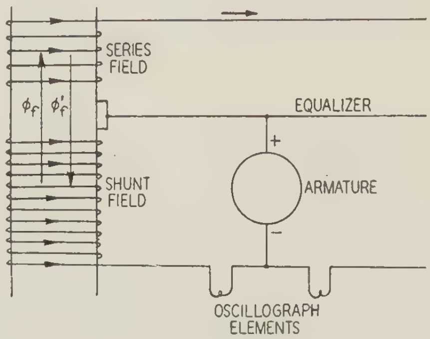


Fig. 4

line current of each generator were in direct agreement with those obtained by Professor Brainerd, October 1932 issue of Electrical Engineering, page 745. Since the prime movers had a drooping speed-torque characteristic, it had to follow that the generator which took the load caused its prime mover to provide a greater torque which, naturally, decreased the speed of that machine. Conversely, the generator that surrendered the load was driven at a higher speed. Although these last tests were made using separate prime movers, the direction of flow of the equalizer current and the sides of the armatures to which the series fields were connected had the same effect upon the distribution of the load between the generators as for the condition with constant speed. It was also noted that the variations of the field and line currents were qualitatively the same for both cases.

On first thought, our 2 sets of results may seem to be contradictory, but upon further analysis they will be shown to be complementary. Under the initial condition (constant speed) we showed that the machine which took the load had an increasing electromotive force; while under the second condition (variable speed) we showed that the speed of the machine which took the load decreased. In both tests, the distribution of the load between the 2 generators was found to depend *only* upon the direction of flow of the equalizer current and the sides of the armatures to which the series fields were connected. It therefore follows that in the second case the machine which took the load had an increasing electromotive force as well as a decreasing speed. Conversely, the generator which lost the load had a decreasing electromotive force and an increasing speed. Since it has been shown that the induced electromotive force

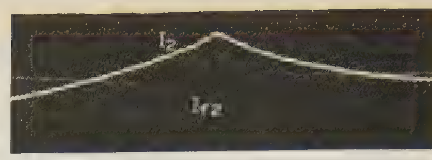


Fig. 5

of the generator that takes the load increases cumulatively, it must be concluded that the increasing electromotive force due to the series field more than overcomes the tendency to decrease that electromotive force which results from the decreasing speed. Even if the series fields were weakened, the results would still be the same. The limiting condition occurs when the generators become undercompounded, in which case the system is stable.

A tabulation of the results, outlined in the foregoing paragraphs, indicates that,

First: Except in the case where zero equalizer current could be constantly maintained, overcompounded generators in parallel are unstable without an equalizer.

Second: Whether a generator will lose the load or take it is dependent only upon the direction of flow of the equalizer current and the polarity of the armature terminal to which its series field is connected.

Third: The effect of the series field in increasing the induced electromotive force, when one of the generators takes the load, more than overbalances the combined tendency to reduce that electromotive force because of a decreased speed and field current.

In attempting to find a theoretical reason that would agree with all of our experimental data, it was found necessary to advance explanations for some conditions which were found to exist but which were not heretofore mentioned in any of the previous discussions.

We hope that this explanation of the problem will help clear up the difficulties which have arisen in its solution.

Very truly yours,

Eric H. Nelson (Enrolled Student) (55 West 184th St., New York, N. Y.)

Sidney Rock (Enrolled Student) (317 East 178th St., New York, N. Y.)

To the Editor:

Within the last few months there have appeared in Electrical Engineering letters concerned with the question of the parallel operation of overcompounded d-c generators. These letters seem to leave the matter in some confusion, which I hope the following lines may serve to clarify. (Previous "Letters to the Editor" on this subject have appeared in Electrical Engineering as follows: by J. G. Brainerd, volume 51, October 1932, page 745; by O. W. Walter, volume 53, November 1934, pages 1553–4; by J. G. Brainerd, volume 54, January 1935, page 135; and by E. H. Nelson and Sidney Rock, this issue, pages 347–8.

The subject which has been under discussion is that of the behavior of overcompounded d-c generators when operated in parallel without an equalizer. It is common knowledge that a condition of unstable equilibrium will exist under such circumstances unless the speed-load characteristics

of the prime movers are more drooping than voltage-load characteristics of the generators are rising. It is axiomatic that if this condition does exist, a small increment to the load of one machine at the expense of the other will precipitate a general transfer of load to the first machine.

Such a transfer may be caused by a momentary increase or decrease of the power input to either prime mover. If an increase, the terminal voltage of the machine will rise due to its momentarily greater speed, it will take additional load, and a general transfer to it will follow, during which the speeds of both machines will be determined by the speed-load characteristics of their prime movers. If a decrease, the terminal voltage of the machine will fall and it will lose its load.

The ultimate cause of the upsetting of balance may not be speed variation, but the variation of some other factor such as field strength. In any case the resulting unbalance of terminal voltage will cause a transfer of load to the generator of higher voltage.

It is seen that a continuous decrease in speed accompanies gain of load; a continuous increase, loss of load. (A drooping speed characteristic is assumed.) However, if the transfer is the result of a momentary speed variation, this variation will be in the opposite direction from that resulting from the load transfer.

In closing I refer to Dr. Harold Pender's discussion in his book "Direct-Current Machinery." As I interpret his reasoning, he gives as the original cause of loss of load an increase of speed, which is very wrong. Such an increase in speed must be followed by an increase in load. No other result is possible.

Very truly yours,

JOHN O. REID (A'34)
(51 Cleveland Terrace,
East Orange, New Jersey)

Accounting and Engineering

To the Editor:

Speaking of "more and better apples"—I refer to J. Allen Johnson's "A Message From the President" printed in the August 1934 issue of ELECTRICAL ENGINEERING, page 1142—it may seem a far cry from accounting to engineering; but I'll hazard the prognostication that the "economic advancement" of engineers, emphasized by President Johnson, is bound up inextricably with accounting considerations.

From this assumption directly flows the conclusion that engineers ought to be personally interested in accounting. Accounting represents, in point of fact, the economic aspect of their professional careers. And I find that engineers are interested when they bother to think about accounting at all.

Once engineers advance in understanding beyond the idea that accounting is arithmetic merely and think of accounting as coextensive with organization, economic organization, which hits them every day at every turn, they do become interested in accounting.

Accounting, in its present state of development, is one half of something. The other half of this something is the engineering, or scientific, outlook upon the physical apparatus upon which all of us are dependent for our economic well being. The name of this something is not yet very definite: cost engineering fits it better perhaps than rationalization, or "technocracy," or even scientific management. The name is of little moment as compared with the large responsibility which faces engineering and accounting. These fields of professional activity must coalesce along their borders where this "something" is sprouting.

Very truly yours,

LEO J. RICHARDS (A'34)
(2818 Shasta Road,
Berkeley, Calif.)

Calculation of Induced Bus Bar Currents

To the Editor:

The paper on "A 7000-Ampere Station Bus" by H. L. Unland, W. B. Morton, and V. R. Bacon in ELECTRICAL ENGINEERING, June, 1934, pages 994–1004, presented very interesting 3-phase test results. One phenomenon observed was that when the 3-phase bus crossed a steel beam, the hottest spot in the beam was under one of the outer conductors and when the phase rotation was changed the hottest spot was under the other outer conductor. This condition was illustrated and calculated by the writer. (See discussion, ELECTRICAL ENGINEERING, December 1934, pages 1646–7.)

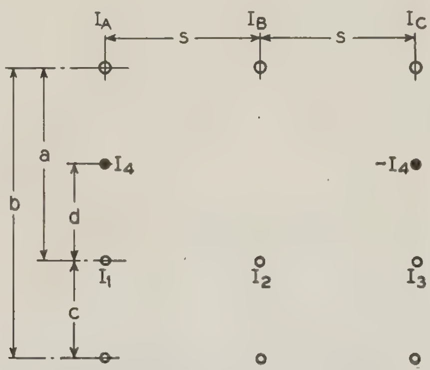


Fig. 1. Arrangement of round conductors

Although the smallest amount of watts might be produced under the central conductor, that need not necessarily be the coolest of the 3 hot spots on the steel beam, since the center one received heat by conduction along the beam from the 2 hot spots which surrounded it.

The calculation on page 1646 did not apply, as mentioned in the discussion by V. R. Bacon, to the test in which a copper plate was interposed between the 3-phase bus and the steel beam, resulting in the hottest spot being changed from one side to the other without the phase rotation being changed. It appears, however, that a similar calculation with round conductors can be made to illustrate this phenomenon also.

Assume the same arrangement of round conductors as on page 1647 and in addition 2 one-inch copper rods forming a short-circuited loop carrying I_4, all as shown in figure 1 of this letter. The lower pairs each form short-circuited loops. The resistance of the rods in these lower loops is R and that of the rods carrying I_4 is R', in abohms per centimeter. The radius of the rods in all the loops is r.

Let the power currents be

$$I_A = (-0.5 + j\,0.866)\,I$$
$$I_B = I$$
$$I_C = (-0.5 - j\,0.866)\,I$$

Taking voltages in the loop carrying I_4 and dividing by $j\omega$,

$$I_A \log_n \frac{4s^2 + (a-d)^2}{(a-d)^2} - I_C \log_n \frac{4s^2 + (a-d)^2}{(a-d)^2} + 2I_4\left(\frac{R'}{j\omega} + \log_n \frac{4s^2}{r^2}\right) + I_1 \log_n \frac{(c+d)^2}{d^2} - I_1 \log_n \frac{4s^2 + (c+d)^2}{4s^2 + d^2} + I_3 \log_n \frac{4s^2 + (c+d)^2}{4s^2 + d^2} - I_3 \log_n \frac{(c+d)^2}{d^2} = 0 \qquad (1)$$

Taking voltages in the loop carrying I_1,

$$I_A \log_n \frac{b^2}{a^2} + I_B \log_n \frac{s^2 + b^2}{s^2 + a^2} + I_c \log_n \frac{4s^2 + b^2}{4s^2 + a^2} + I_4 \log_n \frac{(c+d)^2}{d^2} - I_4 \log_n \frac{4s^2 + (c+d)^2}{4s^2 + d^2} + 2I_1\left(\frac{R}{j\omega} + \log_n \frac{c^2}{r^2}\right) + 2I_2 \log_n \frac{s^2 + c^2}{s^2} + 2I_3 \log_n \frac{4s^2 + c^2}{4s^2} = 0 \qquad (2)$$

These equations and 2 similar ones for the other loops give the loop currents in terms of I.

Let a = 8 inches, b = 12 inches, c = 4 inches, d = 4 inches, r = 0.5 inch, s = 5 inches, frequency = 60 cycles, and the conductivity of the conductors in the 3 lower loops = 20 per cent of that of copper at 20 degrees centigrade.

$$j\,3.43\,I + (11.98 - j\,1.80)\,I_4 + 1.040\,I_1 - 1.040\,I_3 = 0 \qquad (3)$$

$$(0.0372 + j\,0.358)\,I + 1.040\,I_4 + (8.32 - j\,9.02)\,I_1 + 0.989\,I_2 + 0.297\,I_3 = 0 \qquad (4)$$

$$0.1697\,I + 0.989\,I_1 + (8.32 - j\,9.02)\,I_2 + 0.989\,I_3 = 0 \qquad (5)$$

$$(0.0372 - j\,0.358)\,I - 1.040\,I_4 + 0.297\,I_1 + 0.989\,I_2 + (8.32 - j\,9.02)\,I_3 = 0 \qquad (6)$$

Then

$|I_1| = 0.0075\,I$, and $|I_3| = 0.0066\,I$.

It is seen that I_1 is larger than I_3 whereas before the interposition of the loop carrying I_4 which represents the copper plate, I_1 was 6 per cent smaller than I_3, as given on page 1646.

The size of the $^5/_8$ inch air gap between the 2 parts of the square conductor shown in figure 1 of the paper on page 994 is of considerable importance, as stated in the discussions by F. R. Dallye and O. R. Schurig. If this gap were enlarged a little, the copper loss in the metal close to the gap would be larger, but it would be very little altered in the greater part of the conductor.

However, the volume of air rising through the gaps and therefore the convection of heat would probably be changed by a considerable percentage. The relative amounts could be determined only by test. Probably curves of temperature rise plotted on air-gap width, for 5,000, 6,000, and 7,000 amperes, would give the required information in the most convenient form, so that the most advisable size of air gap could be selected.

Similar curves showing the effect of variation in the ratio of depth to breadth of the channels would also be very valuable and might result in savings of space and metal.

If the bus conductors are to be lacquered or painted when in operation, that should be done before testing, as it changes the radiation constant and assists the dissipation of heat.

Very truly yours,

H. B. DWIGHT (A'11, F'26)
(Professor of Elec. Machinery, Massachusetts Institute of Technology Cambridge)

Loading a Bank of Dissimilar Transformers

To the Editor:

The writers were interested to learn that a problem which they had considered as having mainly academic interest is also of sufficient practical importance to warrant the publication of the paper by J. A. Bock on "Loading a Bank of Dissimilar Transformers." (See ELECTRICAL ENGINEERING for December 1934, pages 1597–8.) The paper gives equations for determining the performance of 3 dissimilar single-phase transformers connected to form a delta-delta bank. The transformers may have different impedances and voltage ratios.

Since the problem is essentially one of an unbalanced 3 phase circuit the method of symmetrical components (see "Symmetrical Components," by C. F. Wagner and R. D. Evans, published by the McGraw-Hill Book Company) should provide a convenient solution. This proves to be the case, as is shown in the following discussion.

Let

$\check{I}_0, \check{I}_1, \check{I}_2$ = respectively, the zero sequence positive sequence, and negative sequence components of the transformer secondary currents

$\check{E}_1, \check{E}_2$ = symmetrical components of the secondary terminal voltages

$\check{E}_1', \check{E}_2'$ = symmetrical components of the primary terminal voltages

$\check{Z}_0, \check{Z}_1, \check{Z}_2$ = symmetrical components of the transformer impedances, referred to the secondary sides

These are all vector quantities and are all referred to phase A.

Since the voltage ratios N_A, N_B, and N_C may be unequal, the ratio N_A can be resolved into its symmetrical components $\check{N}_0$, $\check{N}_1$, and $\check{N}_2$, by means of the same well-known relations which are used to resolve impedances, currents, voltages, etc., into symmetrical components. This is a logical but novel idea.

To one familiar with the method of symmetrical components, it is at once apparent that the following 3 vector equations can be set down:

$$\check{E}_1 = \check{N}_0\check{E}_1' + \check{N}_2\check{E}_2' - \check{I}_0\check{Z}_1 - \check{I}_1\check{Z}_0 - \check{I}_2\check{Z}_2 \quad (1)$$

$$\check{E}_2 = \check{N}_1\check{E}_1' + \check{N}_0\check{E}_2' - \check{I}_0\check{Z}_2 - \check{I}_1\check{Z}_1 - \check{I}_2\check{Z}_0 \quad (2)$$

$$0 = \check{N}_2\check{E}_1' + \check{N}_1\check{E}_2' - \check{I}_0\check{Z}_0 - \check{I}_1\check{Z}_2 - \check{I}_2\check{Z}_1 \quad (3)$$

These equations result from the substitution of the symmetrical components in equations 4, 6, 8, and 10 of Bock's paper.

If we assume, as in Bock's paper, that the primary line voltages and the secondary line currents are balanced, then:

$$\check{E}_1' = \check{E}_A' \quad \check{E}_2' = 0, \check{I}_2 = 0$$

and hence, from equation 3:

$$\check{I}_0 = \frac{\check{N}_2\check{E}_A' - \check{I}_1\check{Z}_2}{\check{Z}_0} \quad (4)$$

Equation 4 serves the same purpose as equation 11 of Bock's paper. By means of equation 4 we can calculate $\check{I}_0$ when $\check{E}_A'$ and $\check{I}_1$ are given. Knowing $\check{I}_0$ and $\check{I}_1$, the actual currents in the secondary windings can be calculated by the well-known rules of the method of symmetrical components. The symmetrical components of the secondary terminal voltages can be calculated from equations 1 and 2.

If required, the symmetrical components $\check{I}_0'$, $\check{I}_1'$ and $\check{I}_2'$ of the primary winding currents can be calculated from the following equations:

$$\check{I}_0' = \check{I}_c\check{N}_0 + \check{I}_1\check{N}_2 + \check{I}_2\check{N}_1 \quad (5)$$

$$\check{I}_1' = \check{I}_0\check{N}_1 + \check{I}_1\check{N}_0 + \check{I}_2\check{N}_2 \quad (6)$$

$$\check{I}_2' = \check{I}_0\check{N}_2 + \check{I}_1\check{N}_1 + \check{I}_2\check{N}_0 \quad (7)$$

For the particular case considered in Bock's paper, $\check{I}_2 = 0$. However, this does not mean that $\check{I}_2' = 0$. Because of the unequal voltage ratios of the 3 transformers, negative sequence current will flow in the primary windings even when no negative sequence current is present in the secondaries.

EXAMPLE 1

The data are as given in Bock's paper.

$\check{Z}_A = 0.0290 + j\,0.0983$

$\check{Z}_B = \check{Z}_C = 0.0328 + j\,0.2275$

$\check{N}_A = 0.0667$

$\check{N}_B = \check{N}_C = 0.0697$

By the method of symmetrical components:

$$\check{N}_0 = \frac{1}{3}(N_A + N_B + N_C) = 0.0687 + j_0$$

$$\check{N}_1 = \frac{1}{3}(N_A + \alpha N_B + \alpha^2 N_C), \text{ and}$$

$$\check{N}_2 = \frac{1}{3}(N_A + \alpha^2 N_B + \alpha N_C)$$

where $\alpha = -0.5 + j\,0.866$, and $\alpha^2 = -0.5 - j\,0.866$.

Since $N_B = N_C$,

$$\check{N}_1 = \check{N}_2 - \frac{1}{3}(N_A - N_B) = -0.0010 + j\,0$$

Also

$\check{Z}_0 = 0.0315 + j\,0.1844$

Since $\check{Z}_B = \check{Z}_C$,

$\check{Z}_1 = \check{Z}_2 = -0.0013 - j\,0.0431$

Let $\check{E}_A' = 33{,}000 + j\,0$, and $\check{I}_1 = 455(0.8 - j\,0.6)$, as in Bock's paper.

Substituting in equation 4 gives $\check{I}_0 = 62 + j\,123$. Hence, by the method of symmetrical components:

$\check{I}_A = \check{I}_0 + \check{I}_1 = 426 - j\,150$

$\check{I}_B = \check{I}_0 + \alpha^2\check{I}_1 = -356 - j\,55$

$\check{I}_C = \check{I}_0 + \alpha\check{I}_1 = 117 + j\,575$

These results check Bock's to within slide rule accuracy.

The symmetrical components of the secondary terminal voltages can be calculated from equations 1 and 2, giving:

$\check{E}_1 = 2198 - j\,56$, $\check{E}_2 = -26 + j\,18$

The following problem is an interesting extension of the simple case discussed in Bock's paper, and one which can only be solved by the method of symmetrical components. Consider an unsymmetrical delta-delta connected transformer bank supplying power to an induction motor which we shall also consider as delta connected. At the slip at which the induction motor is operating, its impedances to positive sequence and negative sequence currents are, respectively, $\check{Z}_{m1}$ and $\check{Z}_{m2}$ ohms per phase, delta. Neglect the impedance of the feeder connecting the motor to the transformers. Then

$\check{E}_1 = \check{I}_1\check{Z}_{m1}$ $\check{E}_2 = \check{I}_2\check{Z}_{m2}$

Hence, from equations 1, 2, and 3:

$$\check{N}_0\check{E}_1' + \check{N}_2\check{E}_2' = \check{I}_0\check{Z}_1 + \check{I}_1(\check{Z}_0 + \check{Z}_{m1}) + \check{I}_2\check{Z}_2 \quad (8)$$

$$\check{N}_1\check{E}_1' + \check{N}_0\check{E}_2' = \check{I}_0\check{Z}_2 + \check{I}_1\check{Z}_1 + \check{I}_2(\check{Z}_0 + \check{Z}_{m2}) \quad (9)$$

$$\check{N}_2\check{E}_1' + \check{N}_1\check{E}_2' = \check{I}_0\check{Z}_0 + \check{I}_1\check{Z}_2 + \check{I}_2\check{Z}_1 \quad (10)$$

If the primary voltages are known, these 3 equations can be solved simultaneously for the symmetrical components of the transformer secondary currents. The exact solution is rather awkward to handle.

Let us assume that the primary voltages are balanced. Then $\check{E}_2' = 0$. In any practical case, the term $\check{I}_1(\check{Z}_0 + \check{Z}_{m1})$ will be by far the largest of the 3 terms on the right-hand side of equation 8. Hence, very nearly,

$$\check{I}_1 = \frac{\check{N}_0\check{E}_A'}{\check{Z}_0 + \check{Z}_{m1}} \quad (11)$$

That is, there is little error in computing the positive sequence current as if the transformer bank were balanced and each transformer had an impedance and ratio of transformation equal to the average values of these quantities.

Knowing $\check{I}_1$ we can now solve equations 9 and 10 simultaneously for $\check{I}_0$ and $\check{I}_2$. If we assume, as in Bock's example, that the B and C transformers are alike, then, as shown in example 1 of this discussion, $\check{N}_1 = \check{N}_2$ and $\check{Z}_1 = \check{Z}_2$, and the approximate values of $\check{I}_0$ and $\check{I}_2$ are

$$\check{I}_0 = \frac{(\check{N}_1\check{E}_A' - \check{I}_1\check{Z}_1)(\check{Z}_0 - Z_1 + Z_{m2})}{\check{Z}_0(\check{Z}_0 + \check{Z}_{m2}) - \check{Z}^2_1} \quad (12)$$

$$\check{I}_2 = \frac{(\check{N}_1\check{E}_A' - \check{I}_1\check{Z}_1)(\check{Z}_0 - \check{Z}_1)}{\check{Z}_0(\check{Z}_0 + \check{Z}_{m2}) - \check{Z}^2_1} \quad (13)$$

In a typical case, the error in this approximate solution was found to be less than one per cent.

Very truly yours,

WALDO V. LYON (A'07, F'33)
CHARLES KINGSLEY, JR. (A'30)
(Both of Massachusetts Institute of Technology, Cambridge)

First Electric Street Railway

To the Editor:

In response to your inquiry in the "Letters to the Editor" columns of the February 1935 issue of ELECTRICAL ENGINEERING under "First Electric Street Railway," I desire to call the attention of our sister state of Vermont to the fact that she should be celebrating the centenary of the electric railway, born in the year 1835 in the village of Brandon, Vt.

One Thomas Davenport, village blacksmith, was sponsor. In the Davenport model, motors were driven with current supplied by primary batteries carried on the car. Following Davenport were Robert Davidson, of Aberdeen, Scotland; Prof. C. G. Page, of the Smithsonian Institute at Washington, D. C., and others. All of these experiments were given up on account of the excessive cost of batteries as a source of electrical energy used on the locomotive principle.

In 1847, Prof. Moses G. Farmer operated a small experimental model of an electric car at Dover, N. H., and during 1850–51, aided by Thomas Hall, he exhibited in Boston a model road on which a car ran back and forth, and automatically reversed its direction of motion at each end of the road.

This was one of the first known instances of the use of rails, upon which the car ran, as a means of conveying the current from stationary primary batteries to the motor on the car, and embodied the principle of running the motor at a high speed and gearing it down to a lower speed on the car axle so that a smaller and cheaper motor, for the power supplied, could be used.

At that time the steam locomotive was in its infancy, the law of the conservation of energy was known to but few, and a working knowledge of Ohm's law was confined to mathematicians. The dynamo had not yet been invented.

George F. Green, Kalamazoo, Mich., rescued and revived the abandoned and almost forgotten idea in 1875. He was too poor to buy a dynamo and did not know how to make one.

Siemens and Halske, in Europe, built the first electric railway on a practical scale, using the third rail system, about 1879.

About the same time, Stephen D. Field, in America, was the first to suggest underground conduits, so extensively used in New York.

Thomas Edison did not come into the field until 1880, but did not make any radical improvements.

In May 1881, the first commercial electric road was opened to the public in Lichterfeld, Germany; and the next in 1883, at Portrush, in Ireland. Up to 1883 progress in the direction of commercially developing electric traction was mainly confined to Europe. In 1884 in Cleveland, Ohio, a little later in Kansas City, and in 1885 in Baltimore and Toronto, roads were thrown open to the public. Sprague came into the commercial picture in 1887 with contracts for overhead trolley roads in Richmond, Va., St. Joseph, Mo., and Wilmington, Del. Most of the above mentioned information was obtained from the "Electric Railway Number" of *Cassier's Magazine*, August 1899.

Yours truly,

WALTER S. WHEELER (A' 34)
(Dover, New Hampshire)

Personal Items

HENRY E. WARREN (A'02) president of the Warren Telechron Company, Ashland, Mass., has been awarded the 1934 Lamme Medal of the A.I.E.E. This medal, which will be presented to Mr. Warren at the 1935 summer convention of the Institute which is to be held at Cornell University, Ithaca, N. Y., June 24–28, was awarded him "for outstanding contributions to the development of electric clocks and means for controlling central station frequencies." Mr. Warren was born in Boston, Mass., May 21, 1872, and graduated from Massachusetts Institute of Technology with the degree of bachelor of science in 1894. From 1897 to 1902 he served as electrical and mechanical engineer of the Saginaw Valley Traction Company at Saginaw, Mich. Returning to Boston in 1902 he became engineer and general superintendent of the Lombard Governor Company, which position he held during the next 16 years. In 1904 the factory was moved from Boston to Ashland, Mass. While associated with this company he made improvements in the design of hydraulic speed governors which were installed in many of the largest water power plants of the United States. During the World War he designed several types of hydraulically operated machines which were used in the production of heavy shells and he also developed a new type of fire control mechanism. In 1907 Mr. Warren settled on a farm in the town of Ashland. Here he spent considerable time and thought in designing and constructing various forms of electric clocks as an avocation. One of the farm buildings was converted into a workshop. After several years of experimenting the Warren Clock Company was organized in 1912 to build and sell battery operated clocks. Not satisfied with the product, he undertook in 1916 the problem of utilizing commercial alternating current for the purpose of time-keeping. This involved first, the invention of a new form of self-starting synchronous motor which would be adaptable for use in clocks under conditions quite different from those to which ordinary power motors are subjected; and second, the development of an instrument for measuring frequency with great precision, which later became known as a Warren master clock. Then it was necessary to persuade engineers of power companies to use this instrument so that the frequency of alternating current might be controlled with sufficient accuracy. These objectives were reached before the end of 1916, when the Edison Electric Illuminating Company of Boston adopted the new method of frequency regulation by means of the first Warren master clock. Other companies soon recognized the merits of the idea and within 10 years the use of regulated alternating current as a new kind of time service became general. As a result, the proportion of electric clocks to all clocks exclusive of alarm clocks produced and sold annually has risen from less than 2 per cent in 1916 to more than 60 per cent in 1933 and the increase still continues. Mr. Warren has been engaged since 1916 in adapting time-keeping synchronous motors to many fields of usefulness and in providing improved devices for frequency control. More than 100 patents have been granted to him. During the past 15 years he has served as president of the Warren Telechron Company and consulting engineer for the General Electric Company. He has held several town offices, is actively concerned with the Boy Scouts of America, and has been involved in numerous public enterprises. He has presented several technical papers on the subject of electric time keeping before the Institute and other organizations.

H. E. WARREN

VLADIMIR KARAPETOFF (A'03, F'12, and Life Member) professor of electrical engineering, Cornell University, Ithaca, N. Y., has been awarded the honorary degree of doctor of music by the New York College of Music, New York, N. Y. Professor Karapetoff has been experimenting lately with the phonograph as an accompaniment for the playing of musical instruments, and with making records by combining individual recordings of separate instruments. He has been a member of the Institute's committee on research since 1923 and has served on several other committees, having been chairman of the electrophysics committee 1926–29.

H. C. LEONARD (A'18) since 1930 general superintendent of light and power of the El Paso Electric Company, El Paso, Texas, has been promoted to the position of vice president and general manager of the Gulf

States Utilities Company, Louisiana division, with headquarters at Lake Charles. Mr. Leonard is a graduate of Worcester Polytechnic Institute, and was for a time with the General Electric Company. In 1919 he became connected with the Stone and Webster organization, and in 1927 became head of the engineering department of the Virginia Electric and Power Company at Norfolk. For a short time in 1930 he was head of the electrical department at Richmond, Va.

F. A. Gaby (A'06, F'18) assistant to the president, Canadian Pacific Railway, with headquarters at Montreal, Que., Can., was elected president of the Engineering Institute of Canada at its recent annual meeting in Toronto, Ont. Mr. Gaby received the degree of bachelor of applied science from the University of Toronto in 1904, and subsequently was employed as an erecting engineer by the Canadian General Electric Company, Toronto. In 1906 he became chief assistant electrical engineer on the Pointe du Bois development, Winnipeg, Man., and the following year became assistant chief engineer of the

F. A. GABY

Hydro Electric Power Commission of Ontario. From 1912 until 1934 he held the position of chief engineer, changing recently to his present position as reported in the January 1935 issue of Electrical Engineering, page 140. Mr. Gaby is a member of a number of societies, and in 1930 was representative for Canada to the second world power conference, held in Berlin, Germany. Since 1930 he has been a member of the Edison medal committee of the Institute.

R. W. McNeill (A'13, M'27) formerly engineering supervisor, Westinghouse Electric and Manufacturing Company, Salt Lake City, Utah, is now in the bureau of reclamation of the U. S. Department of the Interior with headquarters at Denver, Colo., and is at present assigned to the inspection of power plant equipment for Boulder Dam and other projects at General Electric Company plants. He has written various articles on electric material handling and mining machinery.

K. E. Estler (A'31) is now associated with the Holophane Company, New York, N. Y., being in training for the position of sales engineer in the New York district. Since graduation from New York University in 1929 he had been with the Electrical Association of New York, which sponsored the Electric Institute (formerly Westinghouse Lighting Institute) and at the time of leaving was chief guide.

J. T. Mountain (A'04, F'20) formerly assistant to the chief operating engineer, Commonwealth Edison Company, Chicago, Ill., has been appointed assistant to the general service manager, a newly established position with duties including supervision of the lamp renewal division and the service bureau.

E. A. Deeds (A'00) chairman of the board, National Cash Register Company, New York, N. Y., has been elected a director of the American Rolling Mill Company, Middletown, Ohio. Colonel Deeds is also interested largely in the General Machinery Corporation, Hamilton, Ohio.

A. O. Summerville (A'23) Malden Electric Company, Malden, Mass., has been appointed superintendent of production, having previously been assistant superintendent and electrical engineer of the company, which is a subsidiary of the New England Power Association.

A. R. Leinbach (A'22) power supply engineer formerly with the Metropolitan Edison Company, Reading, Pa., is now with the New York State Electric and Gas Corporation, Binghamton, N. Y. Both companies are units of the Associated Gas and Electric system.

A. S. Gould (A'26) of Mt. Vernon, N. Y., is now employed as coöperative advisor for the emergency relief administration of the State of California, and is located at Los Angeles.

R. C. Samuels (A'30) of Willows, Calif., is now employed as an electrical engineer by the American Potash and Chemical Corp., Trona, Calif.

G. F. Castellan (A'30) Romford, Essex, England, is not connected with Clements and Son, London, as announced on page 141 of Electrical Engineering for January 1935.

J. K. Johnson (A'28) radio engineer formerly with the Hazeltine Service Corporation, New York, N. Y., is now connected with Wells-Gardner and Company, radio manufacturers in Chicago, Ill.

W. A. Morgan (A'34) is now employed in the substation maintenance department of the Metropolitan Water District of Southern California and is located at Banning.

F. S. Taylor (A'33) formerly assistant field engineer, Henry J. Kaiser Company, Oakland, Calif., is now a junior engineer with the Shell Oil Company, Martinez, Calif.

H. H. Fry (A'34) is now working as a relief operator in the power plant of the Patchogue Electric Light Company at Patchogue, N. Y.

C. A. Poppino (A'30) International General Electric Company, who has been a sales engineer at New York, N. Y., is now office engineer at Schenectady, N. Y.

R. D. Miller, Jr. (A'34) Washington, D. C., is now employed by the National Electrical Supply Company, Washington.

Obituary

Leslie Lawrence Perry (F'22) advisory electrical engineer, Sargent and Lundy, Inc., Chicago, Ill., died at Cuttingsville, Vt., on February 1, 1935. He was born July 13, 1874, at Lawrence, Mass., and was a graduate of Tufts College, receiving the degree of bachelor of science in electrical engineering in 1896. Later, in 1906, he received the degree of master of science. After experience in the engineering and testing departments of the General Electric Company at Schenectady, N. Y., during the period 1897–1900 he went to South America, and was employed by F. S. Pearson (A'92, M'93, deceased 1915), consulting engineer, on the construction of the power and railway systems in the city of Sao Paulo, Brazil. In 1903 he went to Canada, where he was engaged on the construction of the system supplying power from Niagara Falls to Toronto. From 1905 to 1909 he was again in South America, having charge of the electrical design of the power and railway system for Rio de Janeiro, Brazil. The following 2 years were spent in the power and mining department of the General Electric Company at Schenectady, after which Mr. Perry joined the staff of Sargent and Lundy, where he was engaged in the electrical design of large steam power stations, substations, and transmission and distribution systems for cities throughout the United States. He had been advisory electrical engineer since 1930. Mr. Perry had been serving on the Institute's power transmission and distribution committee since 1928, and had presented papers before the Institute. He was also a member of the Western Society of Engineers (Chicago).

William Charles Adams (M'19) consulting engineer, Northern Electric Company, Ltd., Montreal, Que., Can., died January 7, 1935. He was born in Martin County, Minn., September 10, 1880, and was graduated from the University of Minnesota with the degree of electrical engineer in 1905. Following graduation he was employed for a year by the Stromberg-Carlson Telephone Manufacturing Company,

Rochester, N. Y., and then by the Western Electric Company, where he entered inspection engineering work. He followed this through successive positions of responsibility until in 1917 he was in charge of all of the company's engineering inspection work and the clerical and accounting work connected with it. In 1919 Mr. Adams left the Western Electric Company to become chief engineer of the Northern Electric Company, with which he had been connected since, more recently as consulting engineer reporting to the president. In addition to his Institute membership he was a member of the Engineering Institute of Canada, and represented the Canadian Manufacturers Association on the main committee of the Canadian Engineering Standards Association and his company in the American Society for Testing Materials.

George Stafford Gardner (M'32) inspector, excise tax division, tax commission, State of Ohio, Columbus, died in December 1934. He was born at Titusville, Pa., March 11, 1875. In 1900 he was employed by the Home Telephone Company at Dayton, Ohio, and later by the Citizens Telephone Company at Columbus. In 1907 he returned to the former company as assistant engineer and chief inspector in charge of estimates and field work during the construction of the plant at Detroit, Mich. Later he was construction engineer for the United States Telephone Company and the Ohio State Telephone Company, Columbus. From 1920 to 1924 he conducted a private construction engineering business, including street light and traffic signal systems. Mr. Gardner then joined the Hirsch organization in Columbus as associate engineer in charge of all telephone and utility engineering. In 1929 he became superintendent of construction with the Associated Telephone and Telegraph Company, Chicago, Ill., and was engaged in line construction in Colombia, South America, running a 400 mile line through almost impassable country between Buenaventura and Bogota. Since his return to the United States recently he had been employed by the tax commission.

John Edward Donoghue (M'18) managing director, The Electric Light and Power Supply Corporation, Sydney, Australia, died December 28, 1934. He was born at Sheffield, England, December 9, 1871, and studied at Sheffield University. He was employed in England until 1902, when he went to Melbourne, Australia, as a resident engineer for the Melbourne Electric Supply Company, having charge of 2 power houses. From 1906 to 1909 he was chief assistant engineer and acting chief engineer for the Sydney municipal council, and became general manager and chief engineer of the Electric Light and Power Supply Corporation in 1909, when the plant was started, for the design and construction of which he had been responsible. In addition to his duties with this company he served as a consulting engineer for various municipal power plants and industrial companies in Australia. He was appointed to the position of managing director of the company in 1929.

Fred Dunham Emory (A'15, M'27) Portland, Ore., northwest representative, Line Material Company, South Milwaukee, Wis., died November 30, 1934, following an operation. He was born at Winnipeg, Man., Can., May 29, 1891, and after a short period of time with the railway company there attended the Bliss Electrical School at Washington, D. C. In 1911 he returned to Canada and was subsequently employed in a number of companies, including the Canadian Westinghouse Company and the Ferranti Electrical Company of Canada. From 1915 to 1918 he was city electrician at Kaslo, B. C., and until 1921 district inspector of gas and electricity at Nelson, B. C. After 2 years with the Kootenay Power Company, in 1924 he became an electrical engineer in the engineering department of The California-Oregon Power Company, Medford, Ore. Mr. Emory's work for these companies involved the design of power houses, substations, transmission lines, and distribution systems. He had been a representative for the Line Material Company since 1929.

George Dania (A'25) Westfield, N. J., died January 28, 1935. He was born at Ilford, England, July 30, 1895, and received his education at Wembley and London. He was employed in the Metropolitan Railway Company in London from 1912 until 1916, when he became a lieutenant in the British air service. Following the war he formed a partnership in the business of repairing electrical machinery and manufacturing switchgear, and in 1921 joined George Dania, Sr., as assistant engineer, testing and inspecting electrical machinery. In 1924 he became a draftsman in the electrical department of the New York Central Railroad, New York, N. Y., and shortly after took the position of electrical inspector. Mr. Dania went to Cleveland, Ohio, as assistant engineer in the Cleveland Union Terminals Company in 1929, later moving to Lakewood, Ohio, where he remained until recently.

Harry von Turffs (A'31) division superintendent, Montana Power Company, Bozeman, was killed January 15, 1935, in an automobile accident. He was born at Odessa, Russia, March 23, 1886. He studied at the Imperial Gymnasium, Weisbaden, Germany, and at the Naval Academy at Kiel, leaving the latter to go to sea. Since 1909 he had been connected with the Montana Power Company.

Membership

Recommended for Transfer

The board of examiners, at its meeting held February 19, 1935, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Gilt, Carl M., asst. E.E., Bklyn Edison Co. Inc., Bklyn., N. Y.
Hawley, Kent A., chief engr., Locke Insulator Corp., Baltimore, Md.
Hinson, Noel B., chief engr., So. Calif. Edison Co. Ltd., Los Angeles.
Kinsley, Carl, cons. engr., research lab., U.S. Steel Corp., Kearny, N. J.

4 to Grade of Fellow

To Grade of Member

Alden, Dean W., E.E., Blackstone Valley Gas & Elec. Co., Pawtucket, R. I.
Bossemeyer, C. O., gen. mgr., The Rio Grandense Lt. & Pwr. Syndicate, Ltd., Pelotas, Rio Grande do Sul, Brazil, S. A.
Douglas, John F. H., assoc. prof., E.E., Marquette Univ., Milwaukee, Wis.
Elberty, Robert S., Jr., industrial sales dept., Westinghouse E. & M. Co., E. Pittsburgh, Pa.
Freeman, E. D., supt. of elec. dept., Okla. Gas & Elec. Co., Oklahoma City.
Jensen, Marion A., plant engr., Crowell Pub. Co., Springfield, Ohio.
Judd, Robert S., chief engr., Southern New England Tel. Co., New Haven, Conn.
Kane, Edward W., asst. prof., E.E., Marquette Univ., Milwaukee, Wis.
Lemaire, Arthur E., managing elec. engr., Water Conservation and Irrigation Commission, Leeton, N.S.W., Australia.
Lynch, Edward, meter engr., Gen. Elec. S.A., Rio de Janeiro, Brazil, S. A.
MacFarren, Mabel, asst. engr., The Metropolitan Water District of So. Calif., Los Angeles.
Miller, Clarence E., district plant supt., Ohio Bell Tel. Co., Springfield.
Perkins, Edward E., Jr., asst. E.E., U.S. Treasury Dept., Federal Warehouse, Washington, D. C.
Porter, Roland G., assoc. prof. of E.E., Northeastern Univ., Boston, Mass.
Reiber, Albert H., engr. of development and research, Teletype Corp., Chicago, Ill.
Remine, H. H., elec. engr., Montreal Lt., Heat & Pwr. Cons., Montreal, Que., Can.
Snyder, L. G., in charge of engg. and sales, Landis & Gyr, Inc., New York, N. Y.

17 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before Mar. 31, 1935, or May 31, 1935, if the applicant resides outside of the United States or Canada.

Ahlstedt, H. E., Reedsport, Ore.
Albright, D. C., 604 Mott St., Kendallville, Ind.
Andersen, C. J., Gibbs & Hill, N. Y. City.
Anderson, H. H. I., Standard Oil Co. of N. J., Elizabeth.
Anderson, V. J., Western Union Tel. Co., Omaha, Neb.
Andraca, R., Calle 10, 218 Vedado, Havana, Cuba.
Andree, W. A., 462 Pioneer Ave., Glendale, Calif.
Applegrad, A., Western Union Tel. Co., N. Y. City.
Avakian, K. A., Maurice R. Scharff, Mt. Vernon, N. Y.
Ayer, R. W., Simmons Co., San Francisco, Calif.
Baker, J. C., U. S. Elec. Mfg. Co., Los Angeles, Calif.
Barbier, E. G., Ferguson Radio Corp., N. Y. City.
Bassett, E. D., F. W. Sickles Co., Springfield, Mass.
Battit, B. E., Mass. Inst. of Tech., Cambridge.
Bauer, R. V., Montana Pwr. Co., Roundup.
Baumann, F. W., Gen. Elec. Co., Schenectady, N. Y.
Beck, G. P., York, N. Dak.
Bender, J. B., Sky Line Adv. Co., Inc., Oklahoma City, Okla.
Bennett, G. A., Jr., 101 Main St., Ashland, Mass.
Benton, W. T., Pub. Serv. Co. of No. Ill., Forest Park.
Berri, T. L., Southwestern Lt. & Pwr. Co., Lawton, Okla.
Blassberg, A. E., 10 Mechanic St., Shelburne Falls, Mass.
Bliesner, G. H., State Col. of Wash., Pullman.

Blum, R. G., 1500 N. Webster Ave., Scranton, Pa.
Bogen, S., Maurice Scharff, Inc., N. Y. City.
Borgman, T. J., Southern Bell Tel. & Tel. Co., Louisville, Ky.
Botterill, T. L., 4025 E. 19th Ave., Denver, Colo.
Bouchard, J. E. A., Shawinigan Water & Pwr. Co., Three Rivers, Que., Can.
Boyd, R. H., Southwestern Bell Tel. Co., Little Rock, Ark.
Boyd, W., Am. Treibach Chem. Wks., Niagara Falls, N. Y.
Boyle, J. M., 5255 Rodman St., Phila., Pa.
Braunlich, W. E., Braunlich-Roessel Co., Pittsburgh, Pa.
Bremmer, A. J., Gen. Elec. Co., Schenectady, N. Y.
Brian, J. M., Annapolis Metropolitan Sewerage Commission, Md.
Brown, J., 1024 Hill St., Ann Arbor, Mich.
Brubaker, D. G., Penn. R. R., Baltimore, Md.
Bruner, T. W., Standard Oil Co., Milwaukee, Wis.
Bryan, L. B., Louisville Gas & Elec. Co., Ky.
Buchanan, R. O., Univ. of Vt., Burlington.
Buck, H. L., Day & Zimmerman, Inc., Phila., Pa.
Burns, G. K., Western Elec. Co., N. Y. City.
Burr, L. W., Texas Gulf Sulphur Co., Newgulf.
Burt, W. P., Gen. Elec. Co., Phila., Pa.
Byers, R. M., Cons. Gas, Elec. Lt. & Pwr. Co. of Baltimore, Md.
Cairone, A. R., Atlantic City Elec. Co., N. J.
Calhoun, D. R., RCA Victor Co., Inc., Camden, N. J.
Callender, E. M., Am. Hammered Piston Ring Co., Baltimore, Md.
Chambers, C. C., Univ. of Pa., Phila.
Chapman, G. E., 6258 Newark Ave., Chicago, Ill.
Chapman, J. H., Bklyn. Edison Co., Inc., Bklyn., N. Y.
Chun, M. E., Houston Police Station KGZB, Texas.
Clouse, W. W., Penn. R. R. Co., Baltimore, Md.
Colbert, C. J., Potomac Elec. Pwr. Co., Washington, D. C.
Collins, J. G., Clayton Mark & Co., Chicago, Ill.
Cooper, P. G., Jr., Intl. Business Machine Co., Endicott, N. Y.
Corrington, M. S., Kadoka, S. Dak.
Cosentine, M., Eastern Ptg. Corp., N. Y. City.
Coykendall, J. C., Gen. Elec. Co., Bridgeport, Conn.
Crabtree, H. K., New Eng. Pwr. Co., Shelburne Falls, Mass.
Craig, R. L., 4418 N. Whipple St., Chicago, Ill.
Crippen, M. E., Box 133, Pernell, Okla.
Crouter, J. F., Univ. of Mich., Ann Arbor.
Culver, R. L., Clinton Heights, Rensselaer, N. Y.
Cummins, O., Dallas Pwr. & Lt. Co., Texas.
Darrah, J. E., Ohio Pwr. Co., Steubenville.
Day, A. E., Tung-Sol Radio Tubes Inc., Newark, N. J.
Dennis, N. T., Acme Elec. & Mfg. Co., Cleveland, O.
Dick, K. A., Louisville Gas & Elec. Co., Ky.
Dixon, C. R., 31 Greylock Ave., Taunton, Mass.
Dorst, S. O., Sprague Specialties Co., North Adams, Mass.
Ducat, A. C., 218 Springfield Ave., Rochester, N. Y.
Duguid, H. Q., Shell Chem. Co., Pittsburgh, Calif.
Dunlap, G. W., 937 Laurel Ave., San Mateo, Calif.
Edelman, J. E., Route 2, Thiensville, Wis.
Elliott, R. B., 1104 S. State St., Belvidere, Ill.
Erickson, L. H., Pub. Serv. Co. of Colo., Denver.
Fairbanks, J., 186 Temple St., West Roxbury, Mass.
Finger, T., R. H. Bowligny, Inc., Charlotte, N. C.
Fleishman, E., 246—5th Ave., Venice, Calif.
Fletcher, J. F., Courtlaud's (Ltd.), Cornwall, Ont., Can.
Floyd, J. G., Iowa State Col., Ames.
Forman, J., Meyer's Confectionery Store, Bklyn., N. Y.
Foster, R. M., Guardian Elec. Mfg. Co., Chicago, Ill.
Fraker, C. L., Box 116, Pompeii, Mich.
Frankenfield, A. W., Metropolitan Edison Co., Easton, Pa.
Frederick, W. H., Westchester Ltg. Co., Pleasantville, N. Y.
Frenzel, E. E., Freeport Sulphur Co., Port Sulphur, La.
Frick, A. E., Wells Coal Co., Sioux City, Iowa.
Fritz, L. J., Ohio Bell Tel. Co., Toledo.
Fromm, W. H., Jr., Harnischfeger Corp., Milwaukee, Wis.
Fuchs, H. L., Am. Tel. & Tel. Co., N. Y. City.
Funk, A. L., Idaho Seed & Produce Co., Aberdeen.
Gaetjens, A. K., Gen. Elec. Co., Cleveland, Ohio.
Galloway, C. A., 1129 South Ave., Plainfield, N. J.
Gates, R. M. (Member), Superheater Co., & Combustion Engg. Co. Inc., N. Y. City.
Gilmer, J. W., Mont. State Col., Bozeman.
Gonzalez, E. M., Cia. Impulsora de Empresas Electricas, S. A., Mexico, D. F., Mex.
Goodwin, H. B., Harvard Business School, Boston, Mass.
Goss, J. H., Gen. Elec. Co., Lynn, Mass.
Gouchoe, R. L., Central Vt. Pub. Serv. Corp., Rutland.
Gove, E. L. (Member), Radio Air Serv. Corp., Cleveland, Ohio.
Grant, H. A., Jr., 214 Glenwood Ave., E. Orange, N. J.
Graunke, N. C., Home Owner's Loan Corp., Chicago, Ill.
Greenawald, H. E., Stanton Operating Co., Pittston, Pa.
Greidanus, S. C., Holland Furnace Co., Newark, N. J.
Hagopian, H. D., 52 Burnside St., Medford, Mass.
Hampshire, R. A., Ford Instr. Co., L. I. City, N. Y.
Hampson, K., Cumberland High School, Valley Falls, R. I.
Hanan, C. J., Pub. Serv. Co. of Okla., Hugo.
Hancock, J. E., Gen. Elec. Co., Schenectady, N. Y.
Hartman, W. T., 4416—46th Ave., S., Minneapolis, Minn.
Harvey, N. L., Des Moines Register & Tribune, Ames, Iowa.
Hayes, M. V. V., Tidewater Oil Co., N. Y. City.
Heckendorn, H. R., Am. Tel. Co., Hiawatha, Kans.
Heick, B. K., Louisville Gas & Elec. Co., Ky.
Henderson, E. D., Walter Baker Co., Milton, Mass.
Henderson, J. G., Gen. Elec. Co., Schenectady, N. Y.
Herron, J. H. (Member), James H. Herron Co., Cleveland, Ohio.
Hilbert, E. H., % M. R. Scharff, N. Y. City.
Hipple, F. A., Keasbey & Mattiss Co., Ambler, Pa.
Hlavaty, E. M. J., F. I. Tourtelot Co., Chicago, Ill.
Hofmann, P., Potomac Elec. Pwr. Co., Washington, D. C.
Hollister, K. C., Westinghouse E. & M. Co., East Pittsburgh, Pa.
Hunt, H., Carmel, N. Y.
Hutchins, C. N., Gen. Elec. Co., Schenectady, N. Y.
Huyett, S. S., Colo. Sch. of Mines, Golden.
Hynd, R. F., 3482 E. 5th Ave., Vancouver, B. C., Can.
Ingham, P. W., 5800 Halwyn Ave., Baltimore, Md.
Jackson, C. L., Route 2, Sheridan, Wyo.
Jackson, W. L. (Member), Route 3, Colorado, Texas.
Jaeger, J. J., Mass. Inst. of Tech., Cambridge.
Janken, S., C. & H. Sugar Refining Corp., Crockett, Calif.
Janz, W. F., Northern Ind. Pub. Serv. Co., Hammond.
Jarest, J. R., Hillsboro Mills, Wilton, N. H.
Johnson, T. C., Gen. Elec. Co., Schenectady, N. Y.
Johnson, W. C., Gen. Elec. Co., Schenectady, N. Y.
Jones, C. W., Station WJR, Detroit, Mich.
Jones, J. E., Oliver Continuous Filter Co., Oakland, Calif.
Jurasek, F. F., Ford Motor Co., Richmond, Calif.
Kap, F. W., Sanitary Dist. of Chicago, Ill.
Keene, C. L., Ocean Accident & Guarantee Corp., N. Y. City.
Kehoe, J. W., 105 Spring Mill Ave., Conshohocken, Pa.
Kelley, E. K., R.C.A. Radiotron Co., Inc., Harrison, N. J.
Kihn, H., Passaic Evening Vocational Sch., N. J.
Kirker, J. W., Jr., Carrier Engg. Corp., Allentown, Pa.
Klein, M., Ludlow Serv. Station, Yonkers, N. Y.
Klemperer, Dr. Dan (Member), R.C.A. Radiotron Co., Inc., Harrison, N. J.
Klose, H. C., Am. Coal Co. of Alleghany Co., McComas, W. Va.
Koether, G. H., Jr., Round Bay, Severna Park P. O., Md.
Lackey, B. E., Intl. Business Machines, Inc., Endicott, N. Y.
Lamley, R. A., Interlake Iron Corp., Toledo, Ohio.
Lathrop, L. L., Industrial Heater Co., N. Y. City.
Lay, C. R., 36 Madison St., Huntington, Ind.
Leech, K. M., CRI & P Ry., Trenton, Mo.
Lefkowitz, F., United Transformer Co., N. Y. City.
Lepple, H., WLW of the Crosley Radio Corp., Cincinnati, Ohio.
Levy, C. F., U.S. Coast & Geodetic Survey, Norman, Okla.
Lewis, J. H., R. F. D. 4, Fort Collins, Colo.
Libby, C. J., Phoenix Assurance Co., Ltd., N. Y. City.
Lieb, J. S., N. Y. Edison Co., N. Y. City.
Lindheimer, C. M., Potomac Elec. Pwr. Co., Washington, D. C.
Lindholm, P., 329 S. 19th St., Newark, N. J.
Lindquist, R. G., West Penn Pwr. Co., Kittanning, Pa.
Livermore, W. N., 60 Covington Road, Buffalo, N. Y.
Loew, E. A., Ford, Bacon & Davis, Inc., Seattle, Wash.
Lowry, G. F., Consumers Pwr. Co., Grand Rapids, Mich.
Lyons, J. S., 5938 Chester Ave., Phila., Pa.
Mackensen, H. T., Jeffrey Mfg. Co., Columbus, Ohio.
Mackey, S. D., 3 Maple St., Oneonta, N. Y.
MacQuivey, D. R., President Van Buren Dollar S.S. Co., Berkeley, Calif.
Manahan, M. J., 812 Orleans St., Chicago, Ill.
March, L. A., Gen. Elec. Co., Schenectady, N. Y.
Marchett, C., Safety Car Heating & Ltg. Co., New Haven, Conn.
Mary, A. J., La. Motor Fuel Bureau, Baton Rouge.
Mason, C. N., Jr., Green Mt. Jr. Col. & Troy Conference Academy, Poultney, Vt.
Massell, E. M., Maurice Scharff, Inc., N. Y. City.
Mayo, G. E., Jr., Racquette River Paper Co., Potsdam, N. Y.
McCandless, W. H., Lincoln Elec. Co., Cleveland, O.
McClain, F. J., Metropolitan Water Dist. of So. Calif., Indio, Calif.
McDonough, J. B., Firebaugh Canal Co., Mendota, Calif.
McLaren, F. R., Pub. Serv. Co. of N. H., Manchester.
Meckstroth, C. R., United Mills Co., Inc., Grafton, O.
Milewski, L. A., Landers, Frary & Clark, New Britain, Conn.
Miller, T. L., 1308 E. N. Grand Ave., Springfield, Ill.
Minarik, W. J., Bud Radio Inc., Cleveland, Ohio.
Minor, E. E., Jr., Johns Hopkins Univ., Baltimore, Md.
Mitchell, G. E., N. Y. State Elec. & Gas Corp., Binghamton.
Montaudon, R. A., Cia. Mexicana de petroleo, Tampico, Tamps, Mex.
Moore, J. M., United Illum. Co., New Haven, Conn.
Morr, H. S., Utah Pwr. & Lt. Co., Salt Lake City.
Morris, G. C., Sunbeam Elec. Mfg. Co., Evansville, Ind.
Mortensen, H., Kelvinator Corp., Detroit, Mich.
Moses, O. J., Atlantic Refining Co., East Hartford, Conn.
Moskalek, S., Ford Motor Co., Dearborn, Mich.
Mott, G., Jr., Maurice R. Scharff, Mt. Vernon, N. Y.
Mueller, W. S., 22735 Grand River Ave., Detroit, Mich.
Muhl, J., Jr., 584 Albany St., Little Falls, N. Y.
Murbach, J. F., Jr., 563 Senator St., Bklyn., N. Y.
Nelson, C. E. (Member), Phila. Elec. Co., Pa.
Nelson, E. H., Anaconda Wire & Cable Co., Hastings-on-Hudson, N. Y.
Neuhauser, F. L., Louisville Gas & Elec. Co., Ky.
Nisula, W. O., 93 Town Hill St., Quincy, Mass.
Nolan, V. B., Florida Pwr. & Lt. Co., Bradenton, Fla.
O'Brien, A. E., N. J. Bell Tel. Co., Newark, N. J.
O'Brien, G. W., N. Y. Tel. Co., N. Y. City.
Oettinger, C. W., Duquesne Brewing Co., Pittsburgh, Pa.
Oliver, F., 330—6th St., Marietta, Ohio.
Oliver, R. C., Jr., Geophysical Serv., Inc., Kansas City, Mo.
Olson, J. H., Austin Henderson Co., Coeur d'Alene, Idaho.
Orkney, W., Harvard Graduate Sch. of Business, Soldiers Field, Mass.
Owings, A. J., James R. Kearney Corp., St. Louis, Mo.
Packard, R. H., Raytheon Production Corp., Newton, Mass.
Paine, W. E., Rochester Gas & Elec. Co., N. Y.
Parker, C., Indianapolis Street Ry. Co., Ind.
Paschedag, C., Allis-Chalmers Mfg. Co., Pittsburgh, Pa.
Patton, W. L., Calif. Pacific Intl. Exposition, Balboa Park, Calif.
Penn, W. D., Harvard Law School, Cambridge, Mass.
Perez, R. R., 1611—10th Ave., Tampa, Fla.
Peth, H. R., Hoskin Paper Co., Menominee, Mich.
Pettigrew, J., Sansbury Elec. Serv., Florence, S. C.
Phillips, E. H., Bayard, N. Mex.
Plakun, B. D., 552 E. 3rd St., Bklyn., N. Y.
Potter, F. M., Gen. Elec. Co., Schenectady, N. Y.
Pournaras, G. A. (Member), N. Y. Edison Co., N. Y. City.
Pratt, L. C., Forstmann Woolen Mills, Garfield, N. J.
Race, C. R., 31-52—80th St., Jackson Heights, L. I., N. Y.
Raemsch, W. P., Hartford Steam Boiler Insp. & Ins. Co., N. Y. City.
Ranney, N. J., Ferro Enamel Corp., Cleveland, Ohio.
Ray, W. O., Texas A. & M. Col., College Station.
Reuter, P. A., Am. Platinum Works, Newark, N. J.
Reynolds, D. G., Am. Potash & Chem. Co., Trona, Calif.
Reynolds, G. L., 40th & Main Sts., Kansas City, Mo.
Revell, E. F. H., Pa. R. R., Perrysville, Md.
Rhodes, H. A., Humble Pipe Line, Houston, Texas.
Riley, R. C., Leviton Mfg. Co., Bklyn., N. Y.
Rives, G. S., Gen. Elec. Co., Erie, Pa.
Rock, S., Pilot Radio Corp., L. I. City, N. Y.
Rogers, W. E., University Radio & Elec., Berkeley, Calif.
Roseberry, C. V., Westinghouse Elec. & Mfg. Co., E. Pittsburgh, Pa.
Rosenkrans, A. A., Underwriters Lab., N. Y. City.
Ross, H. E., Homestake Mining Co., Lead, S. Dak.
Roy, J., Syracuse Ltg. Co., Inc., N. Y.
Rullman, G. M., Jr., U.S. Industrial Alcohol Co., Curtis Bay, Md.
Safford, F. J., School St., West Chelmsford, Mass.
Sartori, C. J., Jr., Western Elec. Co., Inc., Denver, Colo.
Schlachman, B., 58 Market Place, Baltimore, Md.
Schlang, K., Am. Tel. & Tel. Co., N. Y. City.
Schneider, J. H., Lincoln Elec. Co., Cleveland, Ohio.
Schuchard, E. A., Univ. of Wash., Seattle.
Schwartz, R. D., Gen. Elec. Co., Bridgeport, Conn.
Shockley, T. R., Ga. Pwr. Co., Rome.
Shute, N. (Member), Joslyn Co., Phila., Pa.
Siewert, I. E., Ohio Bell Tel. Co., Toledo.
Sikofsky, G. L., 1206 E. New York Ave., Bklyn., N. Y.
Simpson, C. A., Diesel Engine Commission Sales, Norwalk, Conn.
Simpson, J. M., Town House Garage, Inc., N. Y. City.
Simpson, R. W., Loup River Pub. Pwr. Dist., Columbus, Neb.
Sladen, H. E., Pacific Eastern Gold Mine, Pioneer Mines, B. C., Can.
Smith, C. E., Allen-Bradley Co., Milwaukee, Wis.
Smith, E. W., Gen. Cable Corp., Los Angeles, Calif.
Smith, H. R., Jr., King-Seeley Corp., Ann Arbor, Mich.
Smith, S., Maurice Scharff, Inc., Mt. Vernon, N. Y.
Snively, H. D., Gen. Elec. Co., Schenectady, N. Y.
Snyder, W. W., Niagara Alkali Co., Niagara Falls, N. Y.
Spaulding, R. L., U.S. Engineer's Office, Fort Peck, Mont.
Stachura, E. J., Milwaukee School of Engg., Wis.
Staker, C. R., Vanadium Corp., Niagara Falls, N. Y.
Stampfl, V. F., 67 Woodbine St., Bklyn., N. Y.
Stepien, W. J., 500 Wilson St., Buffalo, N. Y.

Storkerson, J. M., Harvard Graduate School of Business, Boston, Mass.
Straus, F. N., 2613 Queenston Road, Cleveland, Ohio.
Sullivan, W. H., Jr., 3055 So. Santa Fe, Englewood, Colo.
Tesoriero, J. J., Atelier Moderne, N. Y. City.
Thompson, G. R., Samson United Corp., Rochester, N. Y.
Thoresen, P. B., R. I. Elec. Protective Co., Providence.
Tibbitts, D. R., 750 Spruce St., Berkeley, Calif.
Tizian, S. L., 282 Cypress Ave., N. Y. City.
Tolos, P. M., F.E.R.A. Instructor, Clinton, Mass.
Truxal, W. I., 1113 Ross Ave., Wilkinsburg, Pa.
Tudbury, C. A., 39 Bowdoin St., Newton Highlands, Mass.
Turner, J. G., (Member), U.S. Bureau of Reclamation, Denver, Colo.
Ulmer, A. L., Gen. Elec. Co., Fort Wayne, Ind.
Urquidi, A. P., Impulsora de Empresas Electricas, S. A., Mexico, D. F., Mex.
Van Deusen, E. J., Charles R. Vanneman, Inc., Mt. Vernon, N. Y.
Van Nouhuys, H. C., Sunny Service Oil Co., Detroit, Mich.
Villarreal, Leonel Hector, 1116 San Augustin Ave., Laredo, Texas.
Vonasch, R. W., Ill. Bell Tel. Co., Cicero.
Voronzoff, P. I., Gibbs & Hill, N. Y. City.
Wagstaff, R. R., Am. Smelting & Refining Co., Tacoma, Wash.
Wallar, C. H., Continental Oil Co., Rapid City, S. Dak.
Walmer, J., Local Food & Grocery Code Authority, Boro of Bklyn., N. Y.
Walton, J. I., Humble Oil & Refining Co., Houston, Texas.
Waring, S. B., F.E.R.A. Pub. Bldg. Survey Project, Milton, Fla.
Watkins, W. B., Jr., Standard Oil Co., Louisville, Ky.
Wechsler, S., 719 S. 14th St., Newark, N. J.
Weesner, R. J., Taylor Winfield Corp., Warren, Ohio.
Wells, H. N., Jr., Land Policy Section, AAA, Starkville, Miss.
Wentzel, A. B., Norton Co., Worcester, Mass.
Whipker, J. A., Empire Elec. Co., Columbus, Ind.
White, C. K., Gen. Elec. Co., Schenectady, N. Y.
Whitsitt, W. G., Day & Zimmerman, Inc., Phila., Pa.
Wilbor, B., Ford, Bacon & Davis, Inc., Seattle, Wash.
Williams, T. J. C., Gen. Elec. Co., Erie, Pa.
Wilson, R. F., Heintzman & Co., Regina, Sask., Can.
Winckler, G. A., Am. Steel & Wire Co., Boston, Mass.
Wolgast, L. H., Aluminum Cooking Utensil Co., New Kensington, Pa.
Wren, V. R., Hodges-Walsh-Weidner Boiler Co., Chattanooga, Tenn.
Wyss, W. E., Gen. Elec. Co., Schenectady, N. Y.
Young, A., 4213½ University Way, Seattle, Wash.
Zimmermann, K. H., Elite Elec. Serv., Forest Hills, N. Y.

310 Domestic

Foreign

Constad, H., Power Contracts Batwin, Ltd., London, Eng.
Genachte, P. F., 59 Rue Emile Bouilliot, Brussels, Belgium.
Hakim, S. A., British Thomson Houston Co., Ltd., London, Eng.
Knipp, A. R. (Member), Lingnan Univ., Canton, China.
Rodgers, E. J., All Union Aviation Trust of the U.S.S.R., Moscow, U.S.S.R.
Russell, G. D., Kilburn & Co., Calcutta, India.
Strauss, W. A., "Elin," Gesellschaft fur Elektrische Industrie, Vienna, Austria.
Tantawi, M. K. M., Ministry of Education, Egyptian Government, Egyptian Office, London, Eng.

8 Foreign

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the address as it now appears on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Eberhard, Jacob J., 525 Grant St., Santa Clara, Calif.
Fennis, A. M., 4266 Old Orchard Ave., Montreal, Que., Can.
Hansen, A. Fred, 2065½ W. 30th St., Los Angeles, Calif.
Ince, Frank Edward, 2282 Yale Ave., Maplewood, Mo.
Jordan, Arthur H., 5729 Chester Ave., Phila., Pa.
Lemen, Foster M., 3009 Seward, Omaha, Neb.
Mendez, D. P., 6 Division St., Schenectady, N. Y.
Nessler, Aldo E., Delta Starr Elec. Co., 2437 W. Fulton St., Chicago, Ill.
Phillips, R. M., 20 Garth Rd., Scarsdale, N. Y.
Ryden, Eric H., Electrolux Servel Corp., 401 E. 111th St., N. Y. City.
Shirkey, Charles O., 2433 S. Crawford Ave., Chicago, Ill.
Simpson, Sidney, Deputy Loco. Supt., Eastern Bengal R. R., Kanchrapara, Bengal, India.
Skinner, Dean C., 6014 Walnut St., Pittsburgh, Pa.
Travers, James E., 12 Farwell Blk., Claremont, N. H.
Turnquist, F. A., 4 Birch Rd., Wellesley, Mass.
Williams, G. M., 1331 Tonhy Ave., Chicago, Ill.

16 Addresses Wanted

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently, are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

(The) ALLOYS of IRON and COPPER. (Alloys of Iron Research Monograph Series). By J. L. Gregg and B. N. Daniloff. N. Y. and Lond., McGraw-Hill Book Co., 1934. 454 p., illus., 9x6 in., cloth, $5.00. All the essential information upon copper-iron alloys, including a bibliography of 399 articles, selected as most important.

L'ALLUMAGE des MOTEURS a EXPLOSIONS par Bobine d'Industion. (Mises au Point Électrotechniques). By A. Boury and A. M. Touvy. Paris, J. B. Baillière et Fils, 1934. 274 p., illus., 7x5 in., lea., 35 frs. This volume reviews the subject of battery ignition systems for internal-combustion engines, discussing the historic development of ignition systems, the conditions necessary for the ignition of explosive mixtures, and present day methods. Also considered are the principles governing induction-coil ignition, their mathematical representation, and the construction of distributors, ignition coils, etc.

A.S.T.M. TENTATIVE STANDARDS 1934. Phila., American Society for Testing Materials. 1257 p., illus., 9x6 in., cloth, $8.00; paper, $7.00. Contains 236 specifications, methods of testing, definitions of terms, and recommended practices covering materials of engineering, which have been tentatively approved by the society. This relates to metals, ceramic, and concrete materials, paints, petroleum, insulation, textiles, etc. Proposed revisions of standards are also included in the volume.

BESSEL FUNCTIONS for ENGINEERS, N. W. McLachlan. Oxford (England), The Clarendon Press; N. Y., Oxford Univ. Press, 1934. 192 p., illus., 10x6 in., cloth, $5.00. This book aims to provide a course on Bessel functions and their practical applications. No prior acquaintance with these functions is necessary. The theory is simply presented, and many worked examples illustrate the analytical processes and practical applications, with 15 tables of numerical values of functions useful in acoustical and electrical work.

COURS de LÉGISLATION et RÉGLEMENTATION des SERVICES RADIOÉLECTRIQUES. M. Oliver. Paris, Librairie de L'Enseignement Technique, 1934. 181 p., 9x7 in., paper, 25 frs. This textbook, intended for ship or airplane radio operators, covers the laws and regulations governing radio communication and the operation of radio stations, as they affect the operator and his duties.

DIRECT-CURRENT MACHINERY. R. G. Kloeffler, J. L. Brenneman, and R. M. Kerchner. N. Y., Macmillan Co., 1934. 403 p., illus., 9x6 in., cloth, $4.00. This text is intended for junior students in electrical engineering. The theory of direct-current machinery and the applications of direct-current machines are emphasized; but little attention is given to matters of design. The characteristics of this machinery, methods of operation, efficiency, costs, and methods of testing are discussed.

FORSCHUNGSHEFT 368. Mechanische Schwingungen im Maschinenbau. By F. Bielitz and L. Maduschka. Berlin, VDI-Verlag, 1934. 30 p., illus., 12x8 in., paper, 5 rm. In these papers are discussed the inversion of linear mechanical vibrating systems, problems of damping the vibrations of machinery, and a mathematical study of the vibrations of block foundations for machinery.

IONS, ELECTRONS, and IONIZING RADIATIONS. J. A. Crowther. 6 ed. N. Y., Longmans, Green & Co., 1934. 340 p., illus., 9x5 in., cloth, $4.25. This textbook of atomic physics is intended for undergraduate students who have been grounded in the more elementary portions of physics, and desire a systematic knowledge of its later developments.

KOHLEBÜRSTEN zugleich eine Darstellung des veränderlichen Verhaltens der Stromwendung bei Gleichstrommaschinen. J. Neukirchen. Munich and Berlin, R. Oldenbourg, 1934. 135 p., illus., 10x7 in., paper, 6.80 rm. An extensive study of the behavior of carbon brushes in direct-current generators with special reference to the effect of various conditions upon the efficiency of commutation. Commutation and sparking are considered at length, and an explanation of the observed effect of atmospheric changes upon sparking is offered.

Das NEUMEYER-BUCH. Band 1. Die Übertragung von Schwachströmen durch Kabel, deren Bau und Eigenschaften. By H. W. Droste. 2 ed. Nürnberg, Kabel- und Metallwerke Neumeyer Aktiengesellschaft, 1934. 469 p., illus., 9x6 in., cloth, 12.50 rm. This is a manual on the construction and properties of telegraph and telephone cables and their use. It aims to be a textbook for beginners in communication engineering, and also a ready reference work for the engineer. The mathematics of telephone circuits is considered in detail, and in addition a large collection of numerical data is presented in tables and charts.

Die ORTSKURVENTHEORIE der WECHSELSTROMTECHNIK. G. Oberdorfer. Munich and Berlin, R. Oldenbourg, 1934. 87 p., diagrs., 10x7 in., paper, 4.50 rm. The advantages of the polar curve in the solution of alternating current problems are explained, the underlying theory is presented, directions for determining the more important curves are given, and their use illustrated by numerical examples.

PRÉCIS de RÉGLEMENTATION et d'EXPLOITATION des SERVICES RADIOÉLECTRIQUES, Olivier. Paris, Librairie de l'Enseignement Technique, 1934. 120 p., 10x7 in., paper, 20 frs. A manual upon the operation of ship and airplane radio stations, giving the international rules governing the transmission and reception of messages and the regulations adopted at the Madrid and Lucerne conferences with a practical commentary.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a cooperative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

Westinghouse Awarded Steel Mill Order.—The first important steel mill electrification announced in 1935 includes an award to the Westinghouse Electric & Mfg. Co. for part of the electrical equipment to be installed in the McDonald Works of the Carnegie Steel Co., near Youngstown, O. Large d-c motors, totaling 16,000 hp, motor generator sets, and control equipment comprise the bulk of the order. The new mill is expected to be in operation this summer.

New Heavy Duty Brushes.—The National Carbon Co., Cleveland, announces a new series of electrographitic brushes designed especially for service on heavy duty, direct-current equipment. It is stated that this new series is the product of a four year program of research applied to the problem of determining the fundamental physical properties essential to satisfactory brush performance on heavy duty direct-current apparatus, the combination of materials possessing these necessary properties, and exact methods of production control to insure uniformity in both product and performance. The new series is to be known as the "SA" Series of National Pyramid Brushes, and consists of five grades.

Ferranti Increases Voltmeter Range.—According to a recent announcement, the Ferranti electrostatic voltmeter, introduced in this country some time ago, and originally available only up to 3,000 volts, is now supplied with full scales up to 18,000 volts maximum. These high range meters can be furnished in single, dual or triple range types and have numerous applications in present day testing. They consume zero current and the movement is protected with an over-voltage safety device. Electrostatic voltmeters are also now available in $3^1/_4$ and 4-inch dial patterns in full scales up to 3,500 volts. These meters are entirely independent of frequency, wave form, and temperature and may be used directly on either a-c or d-c circuits.

A New Cable Lug.—Supplementing its regular line of clamp type lugs, the Burndy Engineering Co., New York, has introduced a line of clamp wire and cable lugs, known as "Qiklugs," made by a forging process. The advantage claimed for the forged lug is a higher order of strength and conductivity than that possible in the cast lug. Qiklugs are quickly installed by simply inserting the wire or cable in the serrated gripping jaws and tightening a nut. This method of clamping destroys the "barrel effect" by forcing the outer layer of wires against the inner layers, particularly an advantage on the larger sizes of conductors having numerous layers of strands. An Everdur lockwasher, under the tightening nut of similar material, prevents loosening of the connection due to vibration. For temporary installations, the Qiklug can be easily disconnected, providing full salvage value to the terminal. The line of Burndy Qiklugs includes both the one-and two-hole types, of Durium alloy, in all sizes up to 500 mcm. They are approved by Underwriters' Laboratories

Trade Literature

Air-Cooled Transformers. Bulletin GEA-897E, 20 pp. Describes air-cooled transformers for lighting and power service. General Electric Co., Schenectady, N. Y.

Watthour Meters.—Bulletin GEA-615C, 48 pp. Describes standard lines of watthour meters, supplies, and accessories. General Electric Co., Schenectady, N.Y.

Rigid Conduits.—Folder Series. Describes standard thread, protected enameled conduit, electrogalvanized and new hot-dip galvanized conduit with zinc-coated threads. Enameled Metals Co., Pittsburgh, Pa.

Transformers.—Catalog 152. Describes transformers for instrument and metering service; a complete line of current and potential transformers for all voltages as well as combined potential and current transformers or metering outfits. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

Wires & Cables.—Catalog 302-E. A comprehensive brochure describing the processing and including the specifications of a wide range of electrical conductors of many types applicable in utility, industrial and general use. Installations in prominent structures are pictured. Crescent Insulated Wire & Cable Co., Trenton, N. J.

Demand Meters.—Bulletin GEA-612B, 56 pp. Describes the GE line of standard demand meters intended for the measurement of maximum demand (in kw, kv-a, and rkv-a, etc.), and its allied problems. Indicating, graphic, and printing types for all classes of service are included. General Electric Co., Schenectady, N. Y.

Convertible Motors.—Bulletin HM-1. Describes a new line of convertible squirrel cage and slipring induction motors, from $^1/_2$ hp, 600 rpm, to 125 hp, 3,600 rpm. A feature of these new motors is their ready conversion from open type to fan cooled, splash proof or totally enclosed construction. Harnischfeger Corp., Milwaukee, Wis.

Bakelite Varnish.—Bulletin, 40 pp., "Bakelite Varnish, Enamel, Lacquer, and Cement, Heat Hardenable." Describes characteristics, uses, and technic involved in the handling of these materials. In the electrical industry, the Bakelite baking-type liquid products are extensively used for armature and coil impregnation, the coating of paper wound tubes, covered enameled wires, etc. Other applications are illustrated. Bakelite Corporation, Bound Brook, N. J.

Gasoline-Electric Generating Plants.—Bulletin 251A, 4 pp. Describes semi-portable plants with direct current and 60-cycle a-c generators, in sizes from $^1/_4$ to 10 kw; also special lightweight portable plants rated from 650 to 800 watts for power and light supply, and ratings from 300 to 750 watts for furnishing power to the plate and filament circuits of portable radio transmitters. Electric Specialty Co., Stamford, Conn.

Pole Stubbing Clamps for Pole Salvage.—Circular, 4 pp. Describes and illustrates tests of various types of pole stubbing clamps. These clamps are used on poles that have become unsafe at the ground line and are then attached to stubs set in the ground directly adjacent to the original pole. The circular offers to operating companies, with salvage or replacement programs, a sample stubbing clamp set for actual field installation, without obligation. Malleable Iron Fittings Co., Pole Hardware Dept., Branford, Conn.

Thermostatic Bimetal.—Bulletin 301, 20 pp. Describes "Trueflex" thermostatic bimetal, a laminated material, made by fusing two sheets of metal, one having high thermal expansion and the other low. Charts are included for rapidly calculating the proper bimetal elements to accomplish a desired result and the characteristics of each type of material are outlined. General Plate Co., Attleboro, Mass.

Condensers.—Catalog, 24 pp. Describes industrial-purpose condensers or capacitors. One type (oil) utilizes for the dielectric a spacer consisting of two or more layers of paper impregnated with oil and hermetically sealed in cans filled with oil. A second type (electrolytic) utilizes for the dielectric thin films formed electrochemically on the surfaces of pure aluminum foil. The latter are designed for intermittent duty on a-c circuits. The oil condensers are particularly adaptable to continuous use in a-c circuits. Both types are made in a wide variety of standard shapes and sizes or adapted to meet individual requirements. Aerovox Corporation, 82 Washington St., Brooklyn, N. Y.

Battery Float Meter.—Bulletin, 4 pp. Describes the "Exide" float meter, a newly developed device for determining the average voltage of a battery or a direct-current circuit over a definite period of time. The meter operates on the principle of the electrolytic ampere-hour meter with an accuracy of about 0.25%, and draws a current of only 0.004 to 0.010 ampere, depending upon the time between resettings. A particular application of the float meter is in connection with floated batteries where it is desired to maintain a recommended average voltage; such applications include railway signal and interlocking, electric power control, telephone, emergency light and power, and other stationary services. The meter can be used either to determine the actual average voltage being maintained, or to assist the operator through the use of a special calendar scale in maintaining the desired average voltage from day to day. The Electric Storage Battery Co., Philadelphia, Pa.